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EFFECTS OF NITROGEN FERTILIZER PLACEMENT ON UPTAKE UNDER CONTROLLED MOISTURE

BY Murray D. Hartman

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND AND RESEARCH IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

IN

SOIL FERTILITY

DEPARTMENT OF SOIL SCIENCE

EDMONTON, ALBERTA

SPRING 1987

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled EFFECTS OF NITROGEN FERTILIZER PLACEMENT ON UPTAKE UNDER CONTROLLED MOISTURE submitted by MURRAY D. HARTMAN in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE in SOIL FERTILITY.

M Nyborg
Supervisor

Date : April 20, 1987

ABSTRACT

The purpose of this research was to assess the significance of fertilizer positional availability and immobilization under broadcast - incorporated and deep - banded placements. Field rain shelters were chosen to control soil moisture until anthesis, thereby allowing evaluation of the interaction between moisture and placement with respect to the above soil processes , plant fertilizer uptake and barley grain yield. ^{15} N urea (2.408 % atom excess, 50 kg N / ha) was used to follow the weekly fertilizer uptake, and to measure the amounts of fertilizer left in the soil as mineral and immobilized N.

The crude rain shelters proved useful in assessing the effects of fertilizer placement under various moisture regimes. The higher temperatures in the shelters could be reduced by improving the ventilation.

The weekly patterns of fertilizer recovery by the barley plants demonstrated a superiority of deep - banded over broadcast - incorporated placements, especially under early season drought. The higher fertilizer recoveries with deep - banded fertilizer increased plant N content, thus allowing a higher yield potential (increased head number and size) to be set in early growth stages. The improved plant N status also created a larger N reservoir to accommodate N remobilization during grain filling.

Weekly fertilizer recoveries by the plant suggest that with broadcast - incorporation under dry situations, fertilizer remains in dry surface layers and is thus "stranded" from zones of root activity. The anthesis soil data does not support this, but the harvest soil data does. The fertilizer recovery as mineral N in the 0 - 7.5 cm layer at anthesis was suspected to have been underestimated.

Immobilization played a major role in the fertilizer efficiency. By harvest, 55% of the broadcast - incorporated and 40 % of the deep - banded fertilizer

had been immobilized on average. The degree of immobilization appeared to be influenced by the extent of stranding earlier in the season. On average, deep - banding produced significantly more grain than broadcast - incorporation (4515 and 3581 kg / ha respectively). The large yield difference that occurred under early dry situations resulted in a $107 / ha banding benefit. This experiment suggests that deep - band placement should be viewed as a valuable management practice to lessen the adverse impacts of drought.

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I. INTRODUCTION

Field crop production on the prairies is limited mainly by rainfall and nitrogen availability. While dryland crop producers have relatively little influence over the amounts of water available for crop growth, they do have control over the N status of soil through the use of fertilizers. However, the response of crops to N greatly depends on the amounts and timeliness of rainfall.

Research on fertilizer placement techniques has indicated varying efficiencies of crop nitrogen uptake and therefore yield responses. Deep banding is one practice which has gained in popularity during the last decade. Researchers and farmers have emphasized the banding benefit under situations of early season droughts, fall application times and no-tillage cropping systems. Reduced fertilizer efficiency with broadcast-incorporated methods often are attributed to 'stranding' under dry situations, immobilization and denitrification. Relatively few experiments have been conducted to assess the significance of each of these processes with respect to placement and the interaction with moisture.

Thus, the objective of this research was to assess the significance of stranding and immobilization processes in deep-banded and broadcast-incorporated fertilizer placements under controlled moisture regimes. Greenhouse techniques were considered inappropriate for studying the effect of moisture restriction due to the limited soil volume in a pot. Rain shelters were chosen and with the use of ^{15}N, weekly patterns of fertilizer uptake were obtained to evaluate the crop access to fertilizer under the two N placements. Soil fertilizer recoveries were used to measure the extent of stranding and immobilization and to quantify amounts of residual fertilizer.

II. LITERATURE REVIEW

1. Definition of terms

There are two main methods of fertilizer application for field crop production on the prairies (Alberta Agriculture Agdex 542-7-1985):

(a) **BROADCAST** refers to granular or liquid fertilizers which are applied to the soil surface with or without subsequent incorporation. Normal implements on the prairies (cultivators, discers and harrows) mix the fertilizer into the top two to seven centimeters. Where possible, the mode of incorporation shall be specified in this review.

(b) **BANDING** involves placing granular, liquid or gaseous fertilizer into a concentrated row instead of mixing throughout a soil layer. The placement can be conducted prior to seeding (even the previous fall) , in combination with seeding and occasionally post-seeding. There are four general placement geometries:

(i) Drilled with the seed (placement in the seed row).

(ii) Side-banded (to the side and usually just below the seed).

(iii) Deep-banded refers to fertilizer knifed in 7.5-12.5 cm deep, usually in a separate operation from seeding. Anhydrous ammonia application is really a deep banding placement.

(iv) Surface bands are usually liquid fertilizers dribbled in a row on the surface.

An experimental placement which will be mentioned is that of "nesting" or "chutki", and this refers to additional restriction of fertilizer into discrete pockets or points in the soil.

The concept of fertilizer **stranding** refers to the physical isolation of roots from broadcast-incorporated fertilizer under dry situations (no water infiltration to transport the fertilizer to deeper depths). This isolation occurs because the fertilizer remains in the dry surface layers which are unfavorable for root growth and nutrient absorption.

Crop N uptake (kg / ha) refers to the amount of nitrogen, expressed on an area basis, that is present in the aboveground plant parts. This nitrogen comes from indigenous soil supplies (organic matter mineralization), fertilizer applications and seed N .

Fertilizer recovery (%) refers to the amount of fertilizer N recovered in the crop or soil as calculated with isotope dilution techniques (^{15}N). **Residual fertilizer N** is the amount of fertilizer recovered in the total soil N pool (mineral and organic N). **Residual fertilizer mineral N** is the amount of fertilizer recovered in the mineral N (NH_4^+ and NO_3^-) pool. **Immobilized fertilizer N** is the amount of fertilizer recovered in the soil organic pool.

2. Historical overview of fertilizer placement

The practise of applying plant nutrients to improve crops can be traced back to Greek mythology where manuring is mentioned by such writers as Homer, Xenophon and Theophrastus. At that time, soil fertility technology involved animal and green manuring, marling (liming), and wood ash, saltpeter applications.

Scientists in the first nineteen centuries A.D. were preoccupied with attempts to discern plant processes, amounts and types of essential elements. One of the earliest records of fertilizer placement is Nobbe's (1862) work in which enriched soil was arranged in various patterns in cylinders and the effects on root growth noted. Placement research appears to have gained momentum by the middle of this century. Cooke (1954) reviewed experiments on fertilizer placement in England at that time and recommended banding over broadcast application for many crops. In contrast, an American researcher (Nelson 1953) concluded that there was no advantage with banding over broadcast-plowing for furrow irrigated corn. Such conflicting recommendations result from inconsistencies in experimental methods and analyses, as well as the variabilities of climate and soil characteristics. However, subsequent research has provided convincing evidence of a banding benefit (Gasser 1965; Chaudhary and Prihar 1974; Singh *et al* 1976; Alston 1976; Nyborg *et al* 1977; Nyborg *et al* 1979; Yadav and Singh 1982; Harapiak *et al* 1982;

Mengel *et al* 1982; Nyborg and Malhi 1982; Rourke *et al* 1983; Sharma and Chaudhary 1983; Nyborg 1983; Madduxet *al* 1984; Malhi *et al* 1984; Bole *et al* 1984; Mahey and Cheema 1984; Carter and Rennie 1984; Reinertsen *et al* 1984; Hultgreen and Morgan 1984; Harapiak and Penney 1984; Harapiak and Flore 1985; Selles *et al* 1985; Grevers and Voroney 1985; Payton *et al* 1985; Nyborg *et al* 1985; Malhi and Nyborg 1985; Kucey *et al* 1986; Kucey 1986; Jensen and Nyborg 1986; and Dahnke *et al* 1986).

Recent research indicates that further restriction of fertilizer geometry into discrete nests increases uptake efficiency and yields more than banding (Nyborg *et al* 1979; Nyborg and Malhi 1979; Nyborg and Malhi 1982; Nyborg *et al* 1985; Malhi and Nyborg 1985). Relatively few researchers have reported the lack of a banding advantage over broadcast (Yadav and Singh 1982; Papanicolaou *et al* 1983; Nuttall 1985) or of deep banding over surface banding (Deibert *et al* 1985; Alston 1976; Deibert *et al* 1986). Thus research reports are heavily weighted in favor of fertilizer placement over conventional broadcast-incorporated methods. This has prompted recent revision in fertilizer recommendations from the appropriate authorities (for example, see Alberta Agriculture Agdex 542-7 1985).

Establishing the basis of the nitrogen banding benefit has not been as conclusive due to the difficulty of studying N transformations in the field. The commonly cited explanations for the benefit are as follows:

(i) A better physical access of roots to fertilizer is achieved with banding compared to broadcast-incorporation, especially under situations of dry surface soil ("stranding"). An increased water use efficiency of the rooting profile is an important aspect of the stranding concept.

(ii) Less immobilization of fertilizer N into organic pools occurs with placement due to reduced contact area with the soil.

(iii) There are reduced leaching and denitrification losses as a result of slower nitrification in the band and avoidance of the biologically active surface zone.

(iv) Less volatilization losses are experienced with urea and NH_4^+ based fertilizers when placed or mixed into soil compared to un-incorporated surface broadcast applications.

(v) Less ammonium fixation by 2:1 type clays occur when fertilizer is placed.

(vi) There may be reduced weed populations or competition with band placed fertilizer.

(vii) An increased P uptake efficiency is realized when dual banded with NH_4^+ fertilizers.

Fertilizer placement offers advantages to producers other than yield increases. Fall application of fertilizer is often desired because of lower prices, better availability, and more time. No-tillage cropping systems to deter erosion and improve water relations has gained popularity, and in these cases, broadcast-incorporated applications are not effective or possible.

Each of the above reasons will be explored in more detail in the ensuing discussion.

3. Evidence for stranding

Most of the research which studied the effect of water regimes on fertilizer placement uptake efficiency reported an interaction with moisture. Due to the particular relevance to this researcher's project, a recount of pertinent 'stranding' experiments follows.

Nelson (1953) applied N fertilizer by five methods to furrow irrigated corn on virgin soil and then studied the subsequent N distribution in the profile. With banding, NO_3^- was concentrated above the band by capillary action. A more extensive distribution was found with broadcast-plowed N. No yield advantages of placement were reported, but this may have been due to a lack of N response (no controls and a virgin soil), the irrigation method and no true broadcast-mixed treatment (broadcast-plowing results in a type of band).

Cooke (1954) studied fertilizer placement on a number of horticultural and cereal crops in England. He concluded that fertilizers placed or broadcast and

incorporated deeply, are more available to crops in dry years than shallow applications. His evidence was higher yields and root proliferation around the band. The need to have nutrients in soil zones where roots are active was emphasized.

Eck and Fanning (1961) reported increased crop N uptake in a pot experiment with deeper placement under dry conditions, but not under wet. They suggested that with deeper placement the fertilizer zone was more moist, thereby allowing more absorption by roots.

Using irrigated field plots in India, Chaudhary and Prihar (1974) reported faster seedling growth when NPK fertilizer was 20 cm below the seed. They suggested that the vertically growing roots reached the nutrient rich band quickly resulting in better N availability. Roots in the dried surface soil became inactive, and nutrients in this layer were therefore not accessible. The largest banding benefit occurred without irrigation (288%) but a substantial advantage was shown even with added water (48%), implying additional processes such as immobilization. However these researchers stressed the concept of positionally unavailable fertilizer in dry surface layers with broadcast applications.

Singh *et al* (1976) attributed the banding yield increase to the growth of plant roots down for water **and** nutrients from the beginning of growth, resulting in better water utilization. The broadcast application caused root growth in surface soil which later dried, leaving the fertilizer stranded.

Alston (1976), using reconstructed soil profiles and localized restricted water, found that reduced availability of nutrients **after** wheat heading was not a major yield limitation. Placements were compared for depth (5 and 25 cm) but not against broadcast-incorporated application. No effect of depth was noted on root growth, water use efficiency or yield.

Cochran *et al* (1978) found that the yield and protein content of winter wheat increased with deep (60-120 cm) placement when the top one meter of soil was dry at heading. This was attributed to deeper root growth, higher water use efficiency

and prolonged nutrient absorption. Other researchers (Craswell and Strong 1976; Smika and Grabouski 1976) have also observed consistent yield increases from deeply placed N, but no indications were given of topsoil moisture conditions.

Sharma and Chaudhary (1983) studied the root growth, grain yield and water uptake in relation to depth of N placement and moisture regime. Increased root lengths and weights were measured under deep placement compared to broadcast-incorporated. The largest differences occurred in the deeper soil layers under dry conditions. Higher grain yields and better water utilization was attributed to greater root growth in the subsoil due to banding, whereas broadcast-incorporated application stimulated root growth in surface layers which dried. Similar findings have been reported by Mahey and Cheema (1984) where the largest banding benefit occurred in dry years as a result of improved water use.

Bole *et al* (1984) and Carter and Rennie (1984) observed that under very dry field conditions, urea placed 10 cm deep enhanced crop growth and N uptake. The large differences between banding and broadcast-incorporated were attributed to positional unavailability under the latter, although soil mineral N data was not presented to support this. Several other researchers (Harapiak *et al* 1982; Harapiak and Penney 1984; Reinertsen *et al* 1984; Grevers and Voroney 1985; and Kucey 1986) have emphasized the importance of physical access of roots to ferti zer under dry situations.

Jensen and Nyborg (1986) provide further evidence that physical separation of fertilizer and roots can occur under broadcast application in dry no-tillage situations. The banded treatment yielded more, had greater levels of plant N uptake, and lower residual soil fertilizer at harvest than the broadcast treatment. However the residual soil fertilizer N was not clearly specified as to form (organic or inorganic). The residual fertilizer in the broadcast treatment was located mainly in the 0-15 cm layer, thus lending scientific credibility to the stranding concept.

4. Nutrient uptake from bands

In addition to providing evidence that stranding can occur with broadcast N, the means by which plants utilized banded fertilizer needed to be established. The question is: Can a small volume of enriched soil supply the whole plant's needs ?

Cereals have two root types: seminal roots which grow from the primary culm of the plant at seed level after germination; and nodal roots which arise from the main stem at the crown during tillering (Klepper *et al* 1983). These two root types conform to simple patterns of main roots (axes) which bear first order lateral branches, which in turn can produce higher branching orders.

Wiersum (1967) and Burns (1980) state that a relatively small amount of deep roots can sustain a plant, because of an ability to increase uptake rates per unit weight, and usually more favorable subsoil moisture. Other researchers have established the greater uptake rate per unit root weight under localized supply (Gile and Carrero 1917; Hackett 1972; Drew and Saker 1975; de Jager 1984), which helps to compensate for the nutrient deficiency in the remainder of the root system.

In concert with the increased uptake rates of roots under localized nutrients is the proliferation of laterals in such zones, thereby providing greater absorption area (Nobbe 1862; Cooke 1954; Duncan and Ohlrogge 1958; Wilkinson and Ohlrogge 1960; Passioura and Wetselaar 1972; Hackett 1972; Drew *et al* 1973; Drew 1975; Drew and Saker 1975). Together these two factors counterbalance the restricted nutrient supply to the rest of the roots.

Most of the proposed explanations for the increased uptake rates under localized supply involve a feedback mechanism between the shoot and root. A lower shoot nutrient concentration coincides with higher root uptake rates (negative feedback). Both shoot / root carbohydrate ratios and plant growth regulators have been implicated. Pitman (1972b) stimulated the relative growth rate and consequently the nutrient demand of a plant by increasing light intensities, and found increased K uptake per unit root weight. Such regulatory mechanisms must involve messages from shoot to root to effect uptake rate increases. De Jager

(1984) states that the information may be transferred via hormones, photosynthate levels, the nutrient itself or in another form, or substances produced in related amounts during nutrient assimilation. De Jager (1984) favors the concept that the nutrient itself functions as the messenger in the following manner.

Restricting the supply of $H_2PO_4^-$, for example, to part of the root system causes lower shoot $H_2PO_4^-$ concentrations. This lowers the rate of $H_2PO_4^-$ loading at leaf phloem, and less unloading of the phloem in root stele near the xylem poles. Here the decreased $H_2PO_4^-$ concentration stimulates xylem loading (pump two, Pitman 1972a), draining $H_2PO_4^-$ from nearby tissues, increasing the gradient to the absorbing cortical and epidermal cells, thereby lowering the concentration there. Then $H_2PO_4^-$ uptake is increased (pump one, Pitman 1972a). Although this example used $H_2PO_4^-$, Smith (1973) concluded that NO_3^- uptake is regulated by a negative feedback mechanism, and thus the above system could apply.

There has been considerable attention paid to determining the cause of root proliferation in bands. Some researchers have explained the proliferation simply in terms of faster root growth due to better nutrient status (Duncan and Ohlrogge 1958) but more recent research indicates that NO_3^-, NH_4^+ and $H_2PO_4^-$ initiate extensive lateral formation without affecting growth rates of main axes (Hackett 1972; Passioura and Wetselaar 1972; Drew *et al* 1973; Drew 1975; Drew and Saker 1975).

The increased lateral production in enriched soil zones involves a preferential transport of carbohydrates which may be under the control of plant growth regulators (Wilkinson and Ohlrogge 1960; Wilkinson and Ohlrogge 1962; Pitman 1972b; Drew *et al* 1973). Roots encountering enriched soil zones would have increased root nutrient concentrations, protein synthesis and other metabolites which promote lateral initiation, thereby creating "sinks" for assimilates and growth regulators from the shoot. Alternatively, the increased nutrient absorption may

stimulate localized growth regulator synthesis, which then directs assimilates from the shoot to that specific root zone, thus promoting lateral initiation and growth.

In summary, the above evidence demonstrates the plant's ability to obtain its nutrients with a relatively small proportion of roots, thus providing a scientific basis for utilization of banded fertilizer.

5. Immobilization and fertilizer placement

Nitrogen immobilization is the process whereby inorganic N levels decline following the addition of nitrogen poor (<1.2% N) crop residues, resulting in less N uptake by plants and decreased yields (Alexander 1977). This immobilization results from the microbial assimilation of inorganic nutrients and should be regarded as a temporary removal rather than a loss. From an ecological, long-term viewpoint, House *et al* (1984) considers immobilization of N at or near the soil surface in no-tillage systems to recycle N more slowly but more efficiently. However, short term interests of producers dictate that crop uptake efficiencies are of primary importance, and thus immobilization is regarded as an undesirable loss.

Immobilization has been shown to occur less under fertilizer banding than with broadcast-incorporation (Tomar and Soper 1981; Nyborg and Malhi 1982; Carter and Rennie 1984; Heaney *et al* 1984; Nyborg *et al* 1985; Monreal *et al* 1986). Several reasons have been given to explain this difference.

(i) Restricting fertilizer into localized volumes rather than mixing uniformly into the soil reduces the area of contact between fertilizer N and assimilating micro-organisms.

(ii) Placing the band deeper into the soil avoids the biologically active surface zone where straw residues normally accumulate. In this latter respect, no-tillage crop production has greater problems with immobilization of surface applied N (Cochran *et al* 1980; Doran 1980; Fredrickson *et al* 1982; Mengel *et al* 1982; Kitur *et al* 1984; House *et al* 1984; Rice and Smith 1984). In such cropping systems fertilizer placement is regarded as a critical management practice (Mengel *et al*

1982; Carter and Rennie 1984; Grevers and Voroney 1985; Payton *et al* 1985; Jensen and Nyborg 1986).

(iii) The high salt and ammonium concentration in the band slows nitrification and thus the diffusion of mobile NO_3^- to assimilating microbes in the surrounding soil environment.

Thus immobilization plays a major role in affecting the efficiency of N fertilizer, especially with no-tillage systems and fall applications where up to 50% of the fertilizer may be immobilized (Malhi and Nyborg 1983).

6. Nitrification, denitrification and leaching

Alexander (1977) defines nitrification as the biological conversion to NO_3^- or NO_2^- from reduced N compounds. Denitrification refers to the microbial reduction of NO_3^- and NO_2^- resulting in liberation of N_2 and nitrous oxide. From a fertilizer efficiency standpoint, the NH_4^+ form is preferred over NO_3^- due to the latter's susceptibility to losses by leaching and denitrification. However, the trend is toward more fall fertilization and research has shown that NH_4^+ based fertilizers are mostly nitrified by winter's end (Malhi 1978). Consequently denitrification can occur in early spring when surface soils are often saturated.

Nitrification inhibitors have often been successfully employed to reduce overwinter losses of applied N (Gasser 1965; Huber *et al* 1969; Malhi and Nyborg 1982; Malhi and Nyborg 1984), and thus enable higher crop uptakes. Nitrification can also be hampered when N fertilizer is banded or nested (Larson and Kohnke 1946; Gasser 1965; Wetselaar *et al* 1972; Leitch 1973; Nyborg *et al* 1977; Nyborg *et al* 1979; Malhi and Nyborg 1979b; Nyborg and Malhi 1982; Malhi *et al* 1984; Malhi and Nyborg 1984; Malhi and Nyborg 1985; Monreal *et al* 1986). This slower nitrification is due to salt effects (Gasser 1965; Wetselaar *et al* 1972; Pang *et al* 1973), high NH_4^+ concentrations (Wetselaar *et al* 1972; Malhi and McGill 1982), unfavorable pH (Wetselaar *et al* 1972) or possible inhibition by solubilized organic substances (Flaig *et al* 1977; Monreal *et al* 1986). Researchers (Malhi and Nyborg 1979a, Monreal *et al* 1986) have also found that high urea

concentrations impede urea hydrolysis, further delaying the conversion to nitrate. In addition, ammonia toxicity has been shown to slow nitrification as a result of anhydrous ammonia or urea placement (Monreal *et al* 1986).

The adverse conditions present in the band can hinder root development , but such inhibitory effects are short lived (Passioura and Wetselaar 1972). However, some experiments have suggested that nitrite toxicity may occur when urea is banded in high pH soils (Jones and Hedlin 1970; Isensee and Walsh 1971; Passioura and Wetselaar 1972; Wetselaar *et al* 1972; Pang *et al* 1973; Pang *et al* 1977). Pang *et al* (1975) found no NO_2^- accumulation at normal field N rates (<200 kg N / ha). The topic of NO_2^- toxicity due to band placement should be researched further.

Although the reduced nitrification caused by fertilizer placement has been established, there is less direct evidence that banding results in decreased denitrification and or leaching. Field denitrification is difficult to measure, and therefore most of the placement experiments use balance sheet methodology where unaccountable losses are attributed to apparent leaching or denitrification (Nyborg *et al* 1979; Nyborg and Malhi 1982; Malhi and Nyborg 1983; Malhi *et al* 1984; Nyborg *et al* 1985; Malhi and Nyborg 1985). Many of these studies identify fall application times and broadcast-incorporation methods to be more vulnerable to denitrification during spring melt. Nyborg *et al* (1985) recently measured low to high summer losses at several Alberta sites. Therefore denitrification may be important even with spring applications, giving further advantage to the banding practice.

Several researchers have measured less denitrification when bands were placed deep (25-45 cm) , probably because the surface zone with high levels of carbonaceous substrate and denitrifying populations was avoided (Stefanson 1976; Craswell and Strong 1976). One shortcoming in such studies is that denitrification is difficult to separate from volatilization, leaching or plant loss of gaseous N.

Inhibition of nitrification will prolong the existence of immobile NH_4^+ and thus lessen leaching. Researchers generally agree that leaching is not a major mechanism of fertilizer N loss under dryland prairie agriculture (Nyborg *et al* 1977; Campbell and Paul 1977; Tomar and Soper 1981; Nyborg and Malhi 1982; Malhi and Nyborg 1983; Malhi and Nyborg 1984; Heaney *et al* 1984). Thus decreased denitrification losses due to slower nitrification in bands appears to be a major factor in the banding benefit, whereas leaching is not.

7. Volatilization losses and placement

With the increased use of urea and urea-ammonium nitrate solution fertilizers, more attention must be paid to application methods because of their susceptibility to volatilization (Terman 1979). Unless these NH_4^+ based fertilizers are mixed into the soil via incorporation or rain (irrigation), significant volatilization losses can occur (Ernst and Massey 1960; Hargrove *et al* 1977; Terman 1979; Fenn and Miyamoto 1979). The amount of volatilization is influenced by soil organic matter content, cation exchange capacity, soil pH, soil water content, temperature, humidity and N source. However, these factors interact considerably causing difficulties in predicting volatilization losses and diverging research reports (Terman 1979; Bandel *et al* 1980). For example, Mengel *et al* (1982) attributed the higher grain yields and leaf N contents with subsurface N placement compared to surface application under no-tillage and conventionally tilled corn to decreased volatilization or immobilization. In contrast, Maddux *et al* (1984) found that time of incorporation of urea and urea-ammonium-nitrate had no significant effect on grain yield and suggested that little or no volatilization occurred. Rowell (1984) reported small volatilization losses when urea was applied to perennial pastures in Alberta. Such conflicting reports hamper conclusions about the significance of volatilization in pasture, minimum tillage and conventional tillage cropping systems. However, fertilizer banding will practically eliminate volatilization losses, adding even more reasons for banding. No difference is expected between banding and broadcast-

incorporation with regard to volatilization, when the incorporation is immediate and deeper than 2.5 cm.

8. Evidence for less NH_4^+ fixation with banding

The NH_4^+ fixing ability of a soil is generally related to its clay mineralogy. Vermiculite and other 2 : 1 type clays have the greatest capacity for fixation, but montmorillonite should not fix NH_4^+ to any great extent (Nommik and Vahtras 1982). Montmorillonites and other smectites are the most common clay mineral on the prairies so NH_4^+ fixation is not expected to be significant in this region. This attitude is reflected in the paucity of data concerning NH_4^+ fixation under various fertilizer placements. Banding would theoretically reduce NH_4^+ fixation due to less soil contact with fertilizer. Placement would also reduce the exposure to wetting / drying cycles which has been shown to dramatically increase NH_4^+ fixation (Blasco and Cornfield 1966). However, the slowed nitrification in bands would prolong the presence of NH_4^+ and thus could increase fixation. More research could be directed to quantify the significance of NH_4^+ fixation on the prairies and the impact of fertilizer placement upon it.

9. Evidence for reduced weed competition with banding

One benefit of fertilizer placement occasionally suggested is that of decreased weed competition due to selective access to the fertilizer by the crop. Limited research has been conducted to test this hypothesis. Singh *et al* (1976), using a field placement experiment in India found a significant yield response to deep placement. Although broadcasting N was reported to have promoted weed growth, weed populations were not affected significantly. The banding benefit was attributed to more efficient use of water and crop utilization of subsoil moisture rather than reduced weed competition. Payton *et al* (1985) observed an apparent decrease in wild oat populations and a corresponding yield increase when fertilizer was banded 6 cm below the seed. Reinertsen *et al* (1984) reported significantly more wild oat plants under surface broadcast N treatments compared to banding. However, there were no differences at harvest in wild oat dry weights or N uptake,

and thus the increased wild oat population was not considered to have affected crop yields. This research suggests that banding may have advantages with regard to weed competition, but the significance has not been clearly established.

10. Increased P uptake efficiency with dual banding

After researchers and farmers established the potential benefits of N fertilizer placement, interests turned to combining N and P into a single application. At lower N rates, all the N and P was recommended to be placed with the seed. However, as higher N rates became standard practice, a separate operation was required. Researchers in the 1950's (Rennie and Soper 1958; Miller and Ohlrogge 1958) had indicated a marked increase in P utilization when NH_4^+ was present. Subsequent experiments confirmed their findings (Dahnke *et al* 1986; Flaten and Racz 1982). The beneficial presence of NH_4^+ may be due to:

(i) Lowered pH around roots during NH_4^+ uptake, dissolving more P.

(ii) Promoting the increased root proliferation in the band .

(iii) Increasing the root physiological capacity to absorb P.

(iv) Higher ratios of $H_2PO_4^-$ to HPO_4^{-2}.

(v) Increased solubility of fertilizer reaction products.

Harapiak and Penney (1984) found that placement of P in a common band with N was as good as, or better than, seedrow applied P in the Brown, Dark Brown and Thin Black soil zones, especially under moisture stress. Thus the positive N-P interaction provides further incentive for the practice of banding.

11. Producer-related concerns

Farmers often express strong preferences for fall fertilization due to spreading of the workload, less spring tillage, better seedbed quality, more timely seeding, earlier growth, less expensive fertilizer in fall, more available application equipment, and less compaction on the drier fields. Fertilizer banding is especially important for fall applications, since broadcast-incorporated applications have been shown to be susceptible to immobilization and denitrification during spring melt .

Cropping systems have tended away from summerfallow and intensive tillage to continuous cropping and minimum tillage for erosion control and maintenance of soil fertility. As noted previously, fertilizer placement is critical for such systems to be successful. Thus banding appears to be filling a necessary role in the evolution of prairie agriculture.

III. MATERIALS AND METHODS

The experiment was conducted at the University of Alberta Ellerslie Soil Science Research Farm in 1986 (see Appendix 1 for site description). Area of the research plots was 22m X 22m and was cropped the previous year to unfertilized barley. Stubble and chaff remaining from this crop were removed in the spring. Soil mineral N levels to 25 cm were determined in late April to confirm a N - responsive site. Gravimetric soil moisture contents were also obtained at this time.

The experimental design was a split -plot with two replicates. Moisture regimes comprised the main plots and fertilizer placements (plus control or no fertilizer) the subplots. Six moisture regimes were created using rain shelters (until anthesis):

(i) No water until anthesis -- drought conditions (abbreviated as No water)

(ii) 1.0 cm water per week (abbreviated as 1.0 cm)

(iii) 1.5 cm per week (1.5 cm)

(iv) 2.0 cm per week (2.0 cm)

(v) 2.5 cm per week (2.5 cm)

(vi) Natural precipitation (Field)

Each rain shelter (10 in total plus two field plots) corresponded to a main plot, and measured 3m wide by 5m long by 2m high (wall height). A post and beam design was used to build the shelters. The rafters were spaced 90 cm and covered with 6 mill clear construction polyethylene fastened by lath. Ventilation was provided under the eaves, 20 cm above ground level on the sides, and through an open doorway on one end. Water was applied by hand with "soaker hoses" and garden nozzles. The water was supplied from a galvanized sprayer tank and pressure provided with a PTO pump. Uniformity of application was checked in each shelter with graduated plastic cups. Prior to seeding, 5 cm of water was applied to all experimental plots to bring the top 1m of the soil profile closer to field capacity. This watering occurred after all plots had been rototilled twice to a depth of 5-7 cm.

In each rain shelter, N placement subplots were randomized. The fertilizer subplots were deep banded (DB), broadcast-incorporated (BI) and no fertilizer (CON). These subplots measured 1.5 X 2 m with no separation between due to space limitations. However, 1 m of crop was employed as a border between areas of plots used for plant and soil analyses. At least 0.5 m was left between the subplots and sides of the shelters.

Fertilization and seeding were done by hand during the last week in May. Nitrogen was applied at 50 kg N per ha using ^{15}N-urea (2.408 % atom excess), and P at 40 kg P_2O_5 per ha with treble superphosphate (0-45-0). Banding was accomplished by digging a 2.5 cm wide trench, 10-12 cm deep and 2 m long with a mason's hammer. The tagged N fertilizer was uniformly placed in this trench in solution with a 20 ml pipette. Soil excavated from this trench was then replaced and packed lightly by hand. Bands were spaced 20 cm apart and placed directly under the seed row. Broadcast N was applied after seeding in 2 liters of solution with a watering can, then raked into the soil about 2.5 cm deep to simulate harrowing.

The planting operation involved digging a 2.5 cm wide trench, 5 cm deep the length of subplots. Each 2 m trench received 100 Vitavax treated (for smuts) barley seeds (*Hordeum vulgare* var "Galt") spaced 2 cm apart (60 kg / ha), as well as the appropriate amount of phosphate. Water was then sprinkled over the trench and the soil replaced with slight packing. In the banding case, the top 5 cm of soil was left out after the banding to allow for seeding. Fertilization and seeding were done simultaneously for each subplot, beginning with the first replicate and ending with the second. Thus replicate one was seeded three days earlier than replicate two.

The watering schedules noted previously were initiated the week after seeding completion and continued until anthesis (first and second weeks of July). At this stage the roof of each rain shelter was removed . Substantial rain fell very soon after removal of the shelter rooves (Appendix 4).

The experimental plots were used to supply data for two areas of interest : weekly N uptake comparisons and crop uptake plus soil residual fertilizer N.

(i) Plant N uptake patterns were compared between the fertilizer subplots. Weekly plant samples were obtained from the two leaf stage until anthesis which amounted to 5 - 7 weeks, depending upon the moisture regime. Plant material from above the ground surface was collected from 30 cm of crop row, dried at 65°C then weighed. In preparation for N analysis, a portion or all of the dried sample was ground to a fine powder. Nitrogen contents were determined with micro-Kjedahl technique (Bremner and Mulvaney, 1982) using a thiosulphate pretreatment to include NO_3^- (Dalal *et al* 1984). The $^{15}N : ^{14}N$ ratios were measured on a MICROMASS 602D mass spectrometer. Results from these analyses were used to determine crop N contents and fertilizer N recoveries (see Appendix 2 for calculations) which were statistically analyzed by analysis of variance using the Statview statistics software package (Brainpower Inc. 1986). Each week was analyzed separately since a split-split design was not possible with this software.

(ii) At anthesis and harvest, plant and soil samples were taken to enable calculations of fertilizer recovery in each component. Plant samples were handled in the same manner as (i) at anthesis. During the period of grain filling, a light fish net was strung over the crop to deter birds from eating the immature kernels. Harvest samples were obtained from a 1 m portion of a center seed row, and grain was separated from straw and chaff after drying at 65° C. Straw consisted of plant stems, leaves and chaff and the surface 5cm clump of roots (knocked free of soil but not washed). Total N contents and $^{15}N : ^{14}N$ ratios were determined separately on grain and stubble. These analyses were used to calculate grain and straw yields, crop N content and ^{15}N recovery in plant material.

Soil was sampled at anthesis in the following depths : 0 - 7.5, 7.5 - 15, (0 - 15 for controls), 15 - 30 and 30 - 60 cm. Sampling was accomplished using an 18 mm diameter Oakfield sampler with six cores bulked per sample (three cores between and three in crop rows). Slice sampling for the banded treatment was not used due to its destructive nature and the resulting alteration of water infiltration patterns.

Sampling of the soil at harvest occurred at the following depths : 0 - 30, 30 - 75 and 75 - 90 cm (30 - 90 for controls). The 75 - 90 cm depth was employed to indicate leaching of fertilizer N. Sampling methods were similar to those at anthesis.

All soil samples were air dried, ground to first pass a 2 mm sieve then to a powder using a swing mill. Gravimetric moisture contents were determined at the anthesis date. Bulk density measurements on the 0 - 15 and 15 - 30 cm depths were taken after harvest using 7.5 cm diameter plastic pipe. Air dry moisture contents were also determined. Nitrogen analyses on the soils included total N via micro-Kjedahl with thiosulphate pretreatment, inorganic N (NH_4^+ and NO_3^-) on 2N KCl extracts with steam distillation (Keeney and Nelson, 1982), and colorimetric determination of urea (Mulvaney and Bremner, 1979). One soil replicate (harvest, BI, No water, 30 - 75 cm) was not included in the analyses of variance due to spurious results (100% of the fertilizer was calculated to have been recovered in this single soil layer). The cell mean for this treatment combination was used in the statistical analyses and one degree of freedom was subtracted from the subplot error to calculate the F ratios.

The laboratory soil N analyses were used to calculate fertilizer N remaining in mineral and organic forms at both sampling dates, and for fertilizer N recovery (%). The Statview statistical package (Brainpower Inc. 1986) was used to perform analysis of variance tests. Each depth of soil was analyzed separately by ANOVA since the Statview program could not accommodate split-split plot designs. The least significant difference method (5%) requiring a significant F ratio at 5% was chosen for mean separation due to its simplicity and sensitivity in detection of real differences (Carmer and Swanson 1973). The appropriate standard errors of treatment means were used in the calculation of LSD's as illustrated by Little and Hills (1978) and are presented in Appendix 3. The F ratios and their significance (p) are given in Appendix 3a. Least significant differences are tabulated in Appendix 3b.

IV. RESULTS

1. Placement effects on early crop growth

The description of results for the weekly patterns of N content (%), N uptake and fertilizer recovery (%) has been broken down into separate weeks for convenience.

A. Week 1 (three leaf stage).

Averaging over the moisture regimes (Figures 1 to 6), DB produced the highest plant N content (5.73%) during the first week of sampling. BI and the control plots were not statistically different (5.45 and 5.36 % N respectively). When comparing placements in the same moisture level, DB was significantly better than only the CON under the 2.5 cm water (Figure 5) and Field water (Figure 6) regimes. The effect of water and the water-subplot interaction were not significant on N content during the first sampling week.

Placement and nitrogen addition did not significantly affect the crop N uptake (kg / ha) in above ground plant dry matter. At sample week 1, DB plants recovered significantly more fertilizer N, on average, than BI (5.8 vs 1.7% of the applied fertilizer respectively -- see Appendix 6). Within any given moisture level, the differences between placements were not significant. The main effect of water and the subplot-water interaction were not significant.

Week 2 (four to five leaf stage)

At the second sampling week, DB caused significantly higher N content (%) than BI or CON (5.39, 5.10 and 4.99 plant % N respectively) when averaged over all the moisture regimes (Figures 1 to 6). The latter two were not statistically different. Comparing placements at the same water regime, the only significant difference occurred between DB and CON under No water (Figure 1). The main effect of water on N content (%) and the subplot- moisture interaction were not significant.

On average, DB produced significantly higher crop N uptakes than did BI and CON (33, 28 and 26 kg N / ha respectively-- see Appendix 6) at the second week. BI and CON were not statistically different. Comparing at the same water level, DB

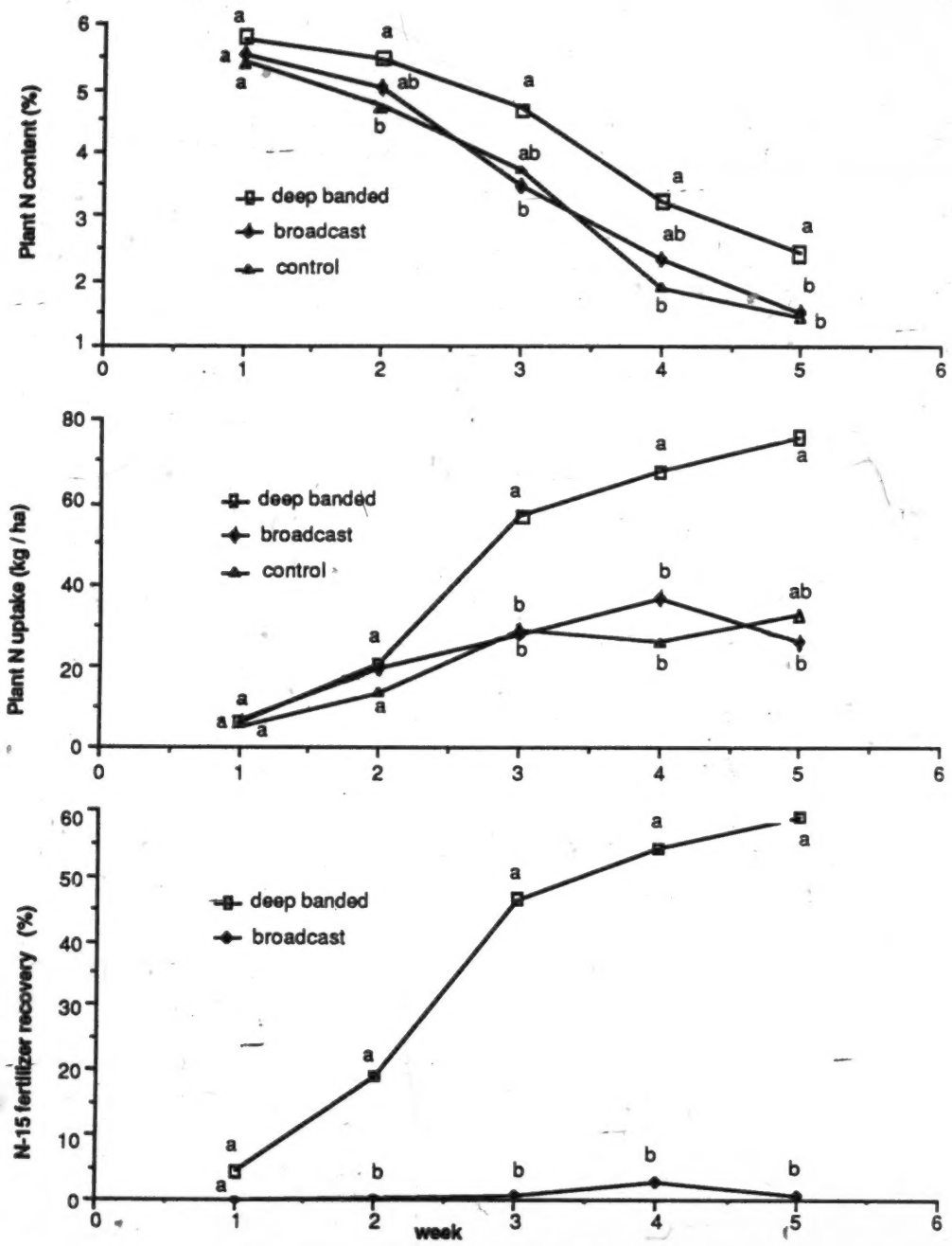

Figure 1. Weekly %N, N uptake and % fertilizer recovery under No water applied until anthesis

Points followed by the same letter in the same week are not significantly different at the 5% level

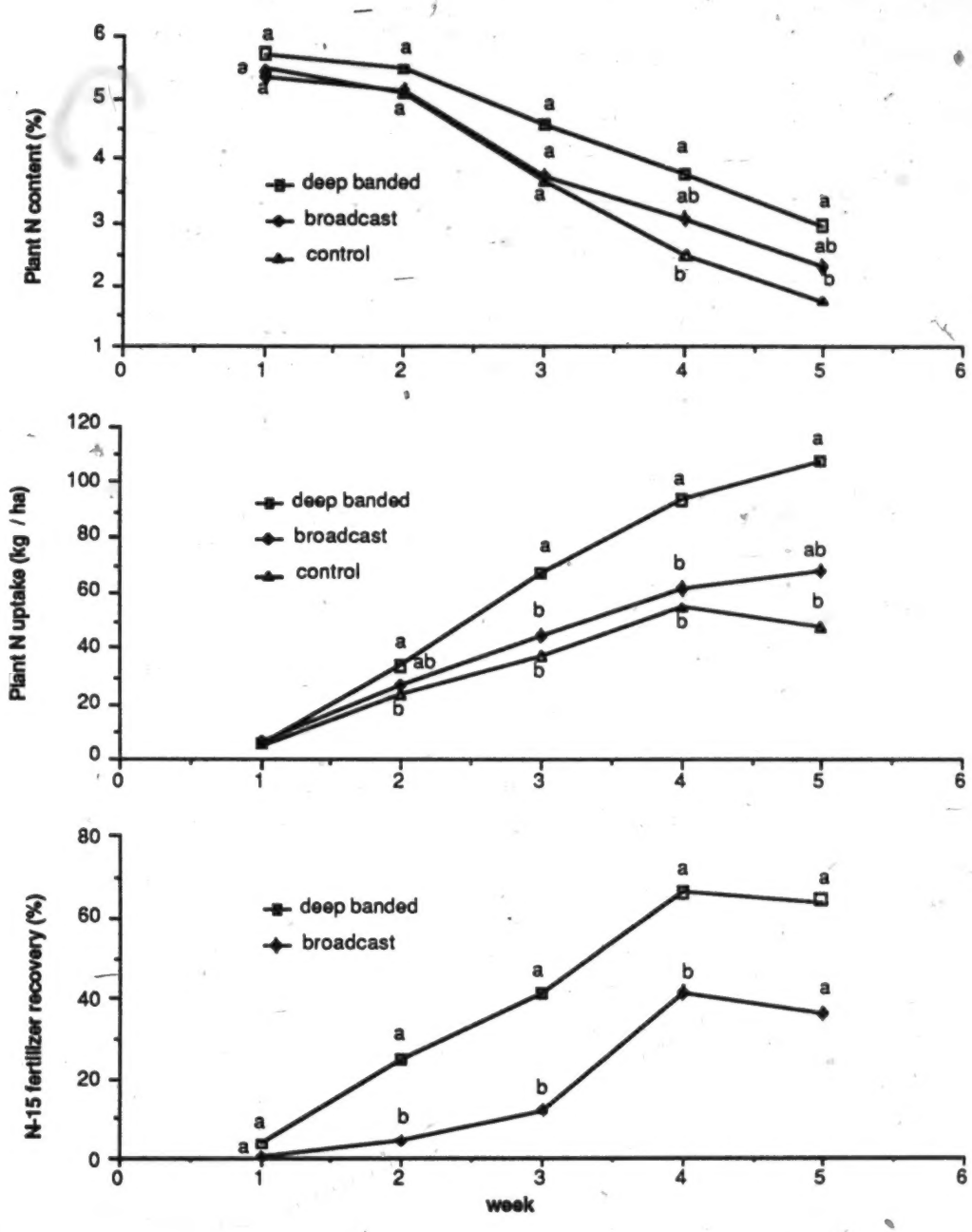

Figure 2. Weekly %N, N uptake and % fertilizer recovery under 1.0 cm water / week until anthesis

Points followed by the same letter in the same week are not significantly different at the 5% level

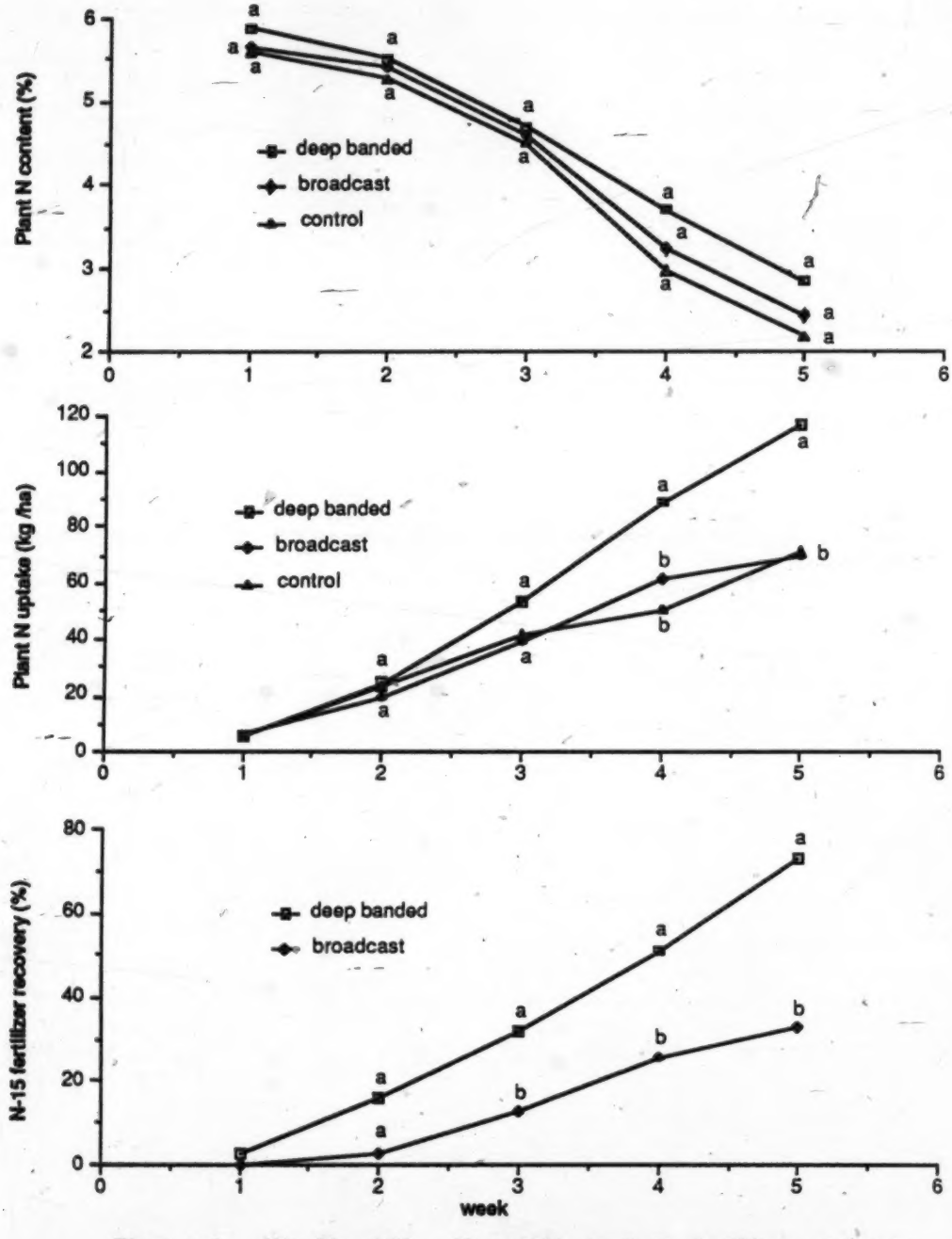

Figure 3. Weekly %N , N uptake and % fertilizer recovery under 1.5 cm water/ week until anthesis

Points followed by the same letter in the same week are not significantly different at the 5% level

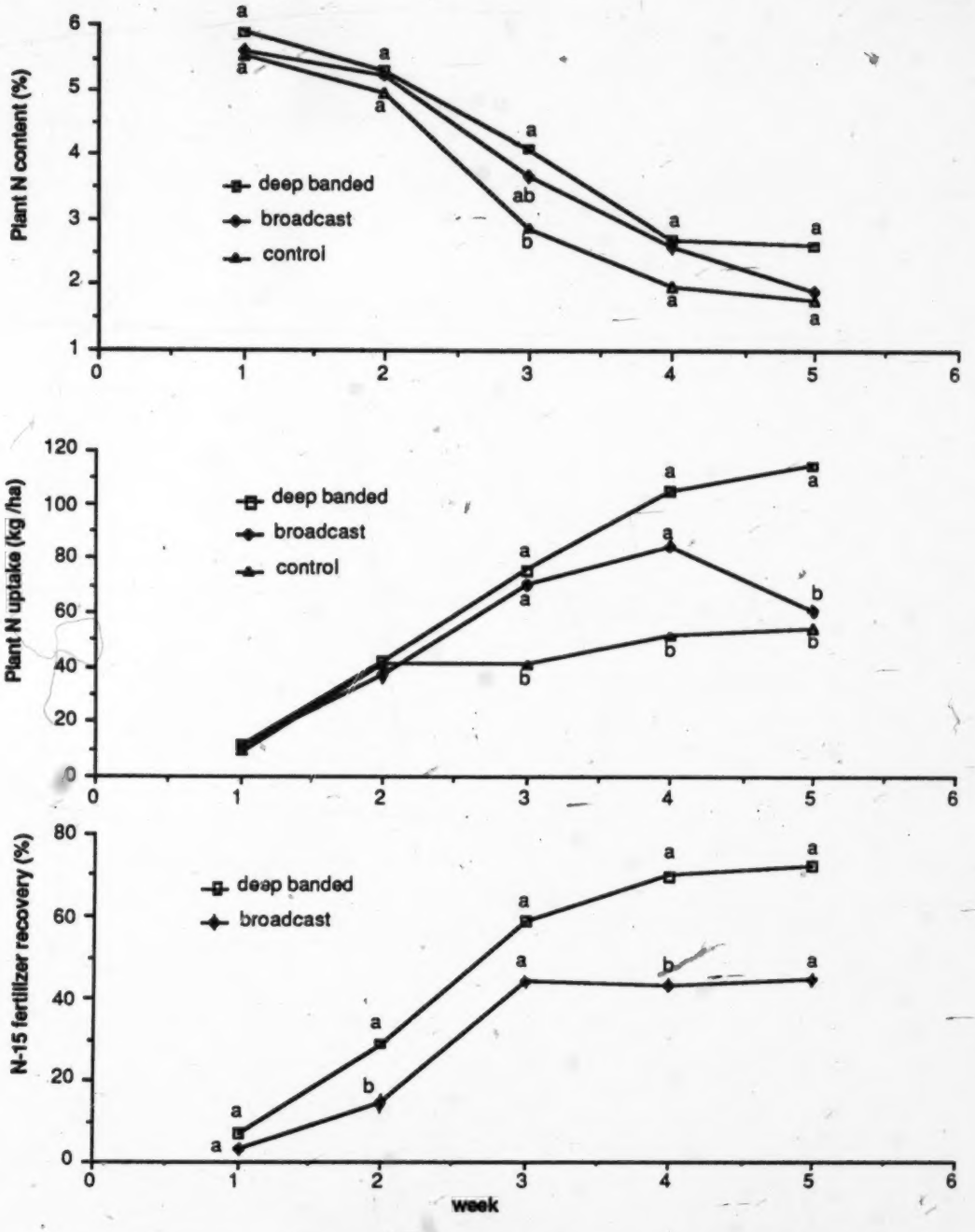

Figure 4. Weekly % N, N uptake and % fertilizer recovery under 2.0 cm water / week until anthesis

Points followed by the same letter in the same week are not significantly different at the 5% level

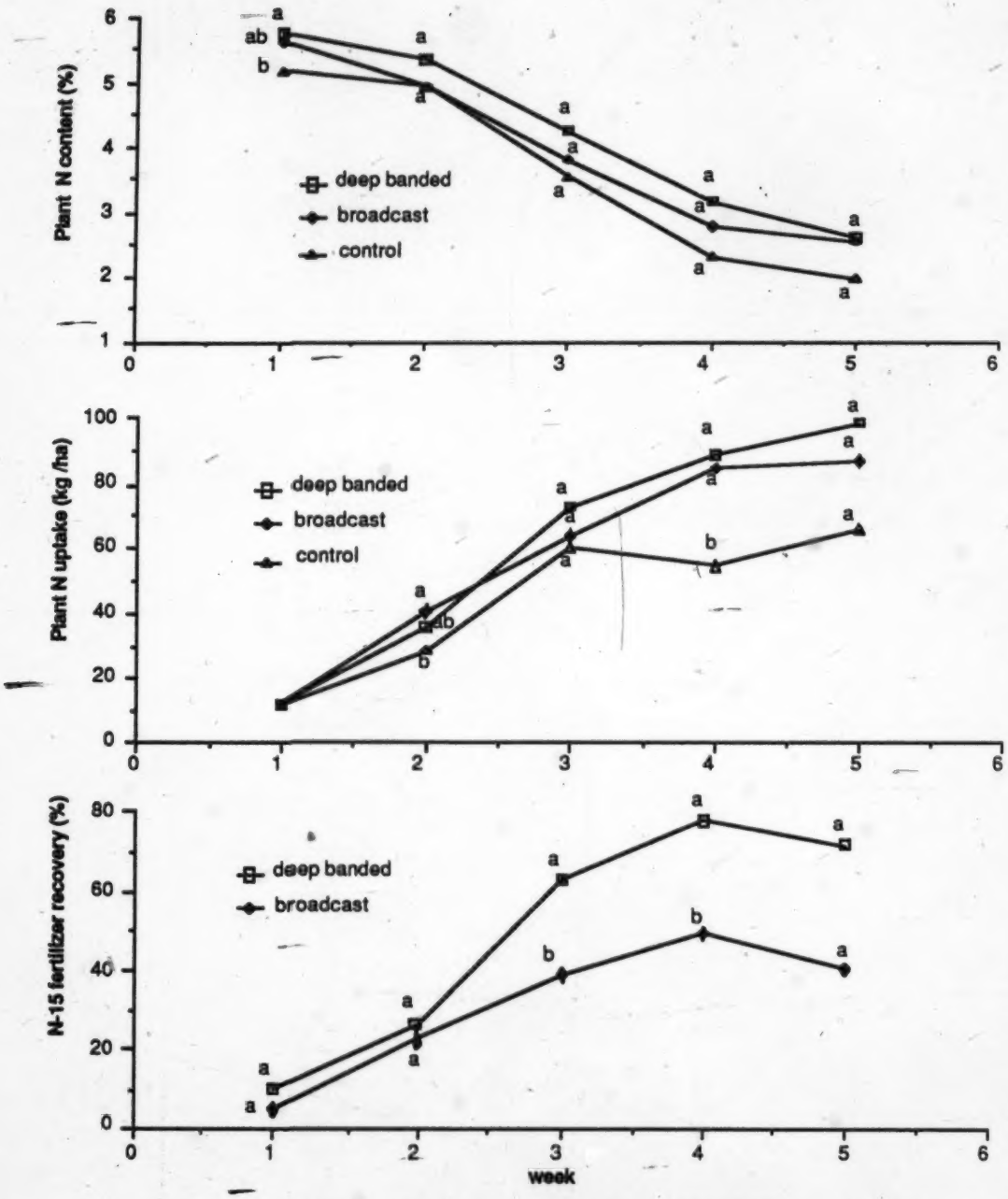

Figure 5. Weekly % N, N uptake and % fertilizer recovery under 2.5 cm water / week until anthesis

Points followed by the same letter in the same week are not significantly different at the 5% level

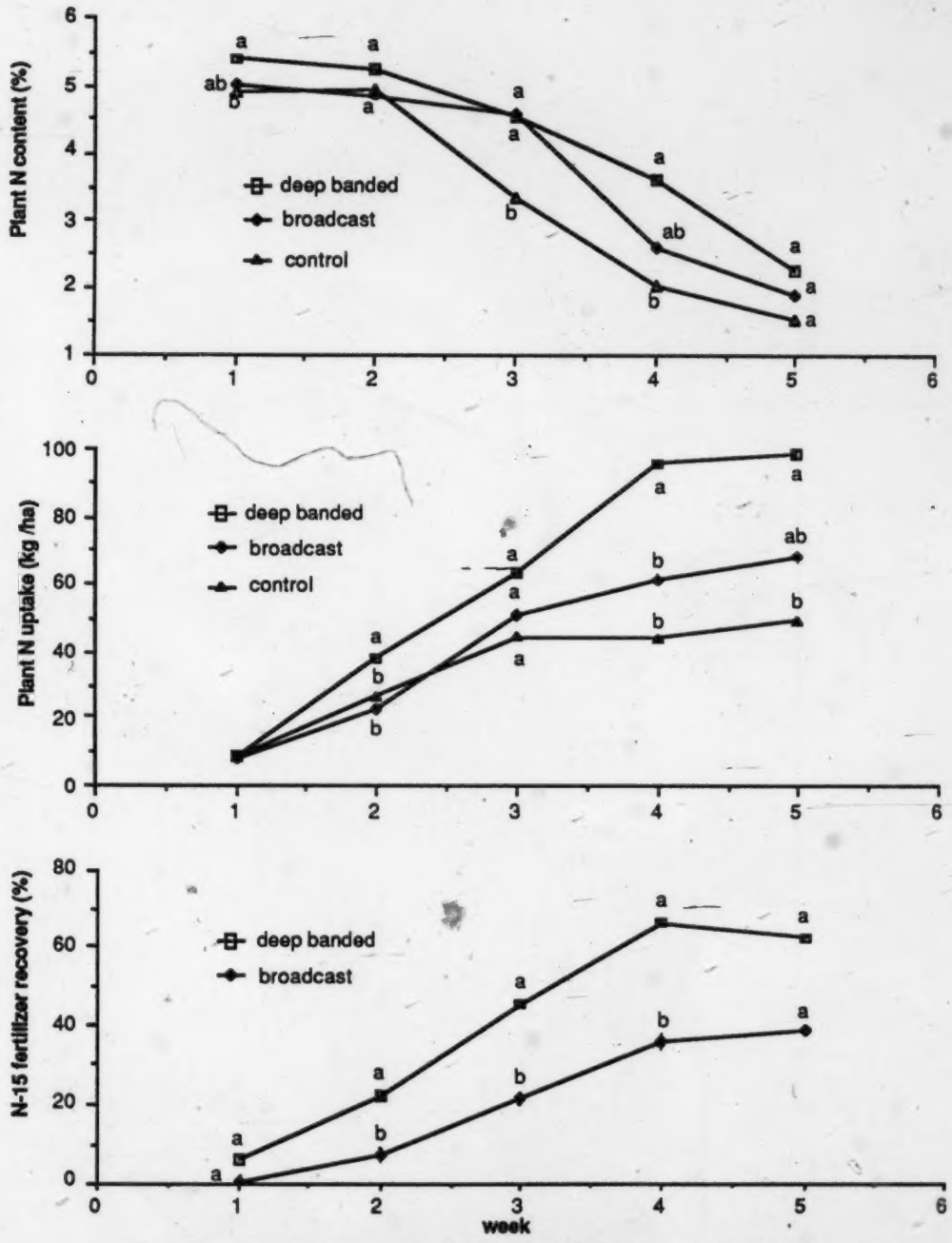

Figure 6. Weekly % N, N uptake and % fertilizer recovery under natural precipitation

Points followed by the same letter or no letters in the same week are not significantly different at the 5% level

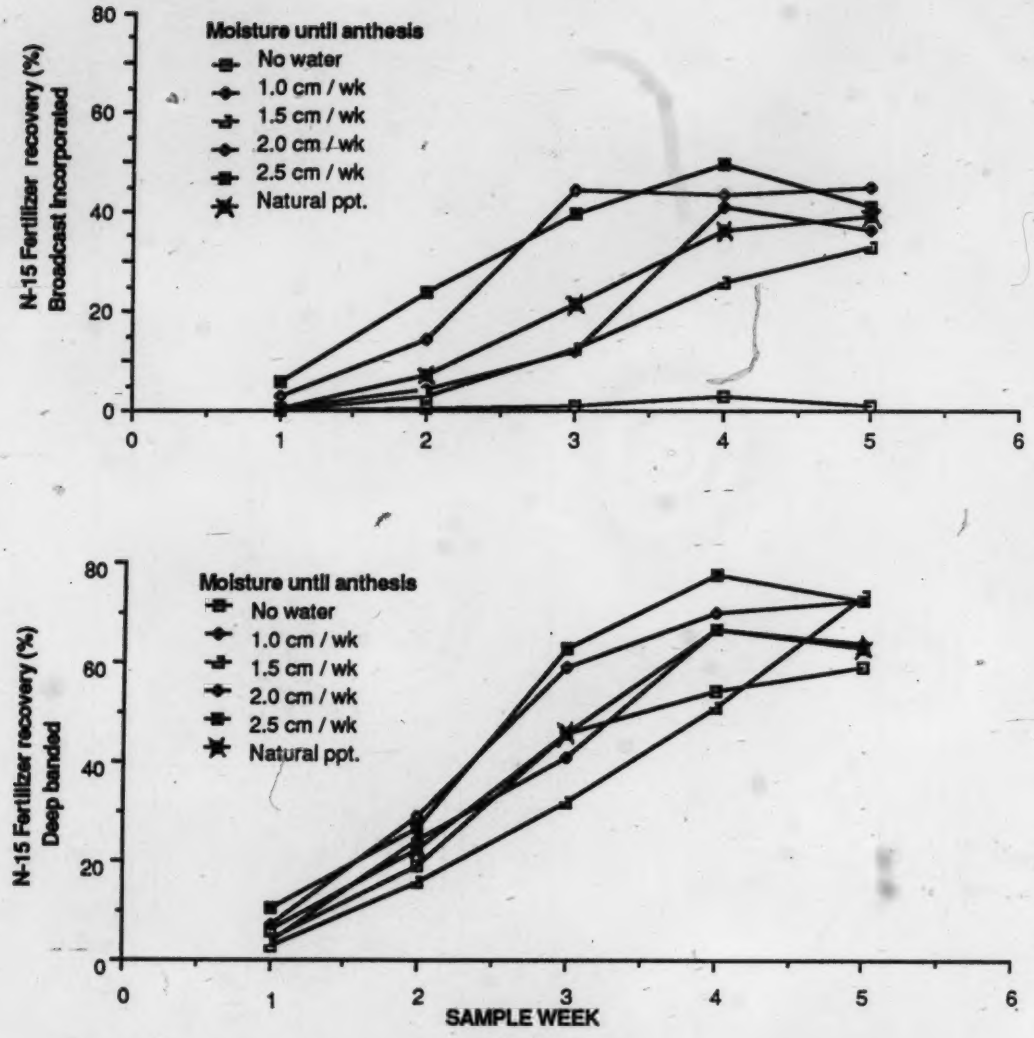

Figure 7. Effect of moisture regime on Weekly N-15 fertilizer recovery (%) under broadcast-incorporated and deep - banded placements

caused significantly higher N uptake than BI and CON under only the 1.0 cm (Figure 2) and Field water (Figure 6) treatments. BI was significantly better than CON only under the 2.5 cm water (Figure 5) regime. No significant interaction between moisture and subplots existed. The main effect of moisture on crop N uptake was not significant.

Averaging over the moisture regimes, DB produced a significantly higher fertilizer recovery at week 2 than BI (22.9 vs 8.8 % of the application respectively--see Appendix 6). When comparing placements under the same moisture level , DB plants recovered significantly more fertilizer than BI under the No water, 1.0 cm, 2.0 cm and Field regimes (Figures 1, 2, 4 and 6 respectively). The main effect of water was significant (Appendix 3a) and higher recoveries of fertilizer N corresponded to higher watering levels (Figure 7). The interaction between moisture and placement was not significant.

Week 3 (six to seven leaf stage)

At the third sampling week, DB produced significantly higher plant N content (%) than BI or CON (4.46, 3.98 and 3.61 % N respectively) when averaged over all the moisture treatments. Comparing at the same water level, DB and BI were significantly different under only the No water regime (Figure 1), and the fertilizer treatments caused significantly higher N content (%) than the CON only under the Field moisture level (Figure 6). There was no significant main effect of water or interaction with fertilizer subplots (Appendix 3a).

Averaging over all the moisture regimes, DB resulted in higher crop N uptakes than BI and CON at week 3 (65, 50 and 42 kg N / ha respectively). When comparing placements at a given level of moisture, DB was significantly better than BI and CON under dry regimes only (Figures 1 and 2). At higher moisture levels (Figure 4) DB and BI were statistically similar and produced higher N uptake than CON. The main effect of water and its interaction with subplots were not significant.

At sample week 3, DB plants recovered significantly more fertilizer than BI (48 vs 22% of the application respectively) when averaged over all the water levels. This

statistical difference was maintained when comparing placements in a given level of moisture except under 2.0 cm (Figure 4). The significant main effect of water (Appendix 3a) showed that fertilizer recovery improved with increasing amounts of water (Figure 7). The water- placement interaction was not significant.

Week 4 (early to late boot stage)

At the fourth sampling week, there was significant differences in plant N content (%) among all three fertilizer subplots when averaged over all the moisture levels (3.36, 2.77 and 2.28 % N respectively for the DB, BI and CON). When comparing placements at the same water treatment, DB and BI were statistically similar, and DB was better than CON only under the No water, 1.0 cm and Field regimes (Figures 1, 2 and 6 respectively). There was not a significant interaction or main effect of water (Appendix 3a).

Averaging over all the moisture levels at sample week 4, DB resulted in greater crop N uptakes than BI and CON (90, 65 and 47 kg N / ha respectively). The latter two were not statistically different. These differences were upheld under dry regimes (Figures 1, 2, 3 and 6) but at higher water levels (Figures 4 and 5) DB and BI absorbed similar quantities of N. The interaction between fertilizer subplot and moisture was not statistically significant. The main effect of water was also not significant but a trend ($P \leq .09$) toward greater N uptake with higher water additions was apparent.

The barley crop recovered significantly more fertilizer with DB (64%) compared to BI (33%) at this stage, averaging over all the moisture levels. This significance was kept when comparing placements under similar moisture levels. The most dramatic disparity between placements occurred under the No water regime (Figure 1) where BI recovered just 3% of the applied fertilizer compared to 54% with DB. The main effect of water was not quite significant but there existed a trend ($P \leq .08$) to higher fertilizer recoveries with more water applied per week (Figure 7). The placement-water interaction was not significant.

Week 5 (anthesis)

Averaging over the moisture levels at anthesis, DB caused significantly higher plant N content (%) than BI or CON (2.64, 2.12 and 1.78 % N respectively). The latter two were similar statistically. This relationship was maintained at No water and 1.0 cm water regimes (Figures 1 and 2) when comparisons are made within the same moisture level. The interaction of fertilizer subplot with water was not significant.

DB resulted in significantly greater crop N uptakes than BI and CON when averaged over all the water levels at anthesis (102, 63 and 53 kg N / ha respectively). The latter two were statistically similar. When comparing subplots under similar moisture regimes, DB allowed greater N uptake than BI at the 1.5 and 2.0 cm water levels (Figure 3 and 4). DB produced higher N uptakes than the CON in each moisture regime except for 2.5 cm (Figure 5). There was no significant interaction or main effect of water in N uptake at this stage. Replicate 1 (earlier seeded) had statistically higher in N uptake than replicate 2 (Appendix 3a).

Averaged over the moisture levels at anthesis, DB plants recovered significantly more fertilizer (67%) than BI (32%). DB was better statistically than BI only under the No water and 1.5 cm water regimes (Figures 1 and 3) when comparing placements within the same moisture level. The interaction of water and placement was not significant . The main effect of water was significant (No-water regime experienced less fertilizer recovery than all others). Negligible fertilizer was recovered by BI (1%) under No water (Figure 1), compared to 60% recovery by DB. Replicates differed significantly in fertilizer recovery at anthesis (R1 > R2).

2. Placement effects on soil moisture contents at anthesis

0-15 cm depth

A significant difference existed between fertilizer subplots in soil moisture contents (mass basis) at anthesis in this soil layer when averaged over all the water levels (Table 1). BI produced lower moisture contents than the CON but not DB. There was a significant effect of water regime which showed a consistent increase in soil moisture with higher weekly watering increments. The Field treatment had the

highest moisture content due to a rain prior to sampling. Comparing placements within identical water regimes, BI and DB removed more soil moisture than CON by anthesis only under the 2.5 cm treatment, and BI was drier than the CON also under the Field conditions.

15-30 and 30-60 cm depths

None of the fertilizer subplots differed significantly in soil moisture contents at these depths by anthesis. In the 15-30 cm depth, there was a significant effect of water additions per week on soil moisture contents, similar to the surface soil layer. In the 30-60 cm depth , the effect of moisture regime on soil water content was not significant. The interactions of subplot with moisture were not significant.

Table 1. Effect of FertilizerPlacement on Gravimetric Soil Moisture (%) at Anthesis

		Moisture Regime (cm water / week until anthesis)						
Depth (cm)	Subplot	No water	1.0	1.5	2.0	2.5	Field	Mean
		----------	----------	----------	----------	----------	----------	----------
	CON	14.9 a	18.0 a	20.3 a	23.5 a	28.3 a	36.4 a	23.5 a
0-15	BI	14.9 a	16.5 a	21.0 a	22.2 a	24.2 b	32.4 b	21.9 b
	DB	16.1 a	17.2 a	19.7 a	23.2 a	24.0 b	34.3 ab	22.4 ab
	Mean	15.3 A	17.2 AB	20.3 BC	22.9 CD	25.5 D	34.4 E	22.6
	CON	16.1 a	16.9 a	19.4 a	20.7 a	22.4 a	32.4 a	21.3 a
15-30	BI	15.6 a	16.4 a	20.2 a	19.7 a	19.8 a	33.6 a	20.9 a
	DB	17.0 a	17.5 a	19.7 a	22.5 a	18.3 a	33.6 a	21.4 a
	Mean	16.2 A	16.9 A	19.7 AB	20.9 B	20.2 B	33.2 C	21.2
	CON	12.6 a	12.8 a	14.4 a	14.2 a	14.3 a	15.3 a	13.9 a
30-60	BI	11.0 a	12.4 a	13.8 a	13.9 a	13.8 a	17.5 a	13.7 a
	DB	12.9 a	12.7 a	13.2 a	15.0 a	14.0 a	18.3 a	14.3 a
	Mean	12.1 A	12.6 A	13.8 A	14.4 A	14.0 A	17.0 A	14.0

Values in the same column for the same depth followed by the same lower case letter are not significant at the 5% level
Mean values in the same row followed by the same upper case letter are not significant at the 5% level.

3. Placement effects on soil fertilizer recovery at anthesis

Total soil depth (0-60 cm)

At anthesis, there was not a significant effect of placement on the amount of residual fertilizer N in the soil profile (Figure 11). Water regimes tended ($P \leq .06$) to affect the quantity of fertilizer remaining in the profile -- highest residual fertilizer N was associated with the lowest watering schedules, including Field. On average, about 40% of the applied fertilizer remained in the soil at this stage.

On average, approximately three quarters of the residual fertilizer occurred in organic forms (Figure 8). A significant difference existed between placements averaging over the moisture levels; DB resulted in less immobilized N than BI (23% vs 35% of the applied fertilizer respectively). When comparing placements within the same water level, BI showed significantly more immobilization under the 2.0 cm and Field moisture regimes only. There was not a significant interaction or water effect. The Field-BI combination had the most immobilization (56% of the applied fertilizer).

Averaging over the moisture treatments, there was no significant placement effect on the amount of fertilizer N remaining as mineral N at anthesis (Figure 8). Watering levels significantly influenced the quantities of residual fertilizer mineral N -- the No water regime left more fertilizer N in the mineral forms than any other moisture level.

0-7.5 cm depth

On average at anthesis (Figure 9), BI resulted in more residual fertilizer N in this soil layer than DB (30 vs 14 % respectively). There was not a significant interaction of placement and moisture. Water alone had a significant effect on the amount of residual fertilizer N in this layer ; the highest soil fertilizer N recoveries occurred under low moisture and Field regimes. As much as 45 % of the fertilizer application was detected in this soil layer at anthesis under the BI -Field plots, but just 10% under DB-Field . Replicates differed significantly in amounts of residual fertilizer N in this soil layer.

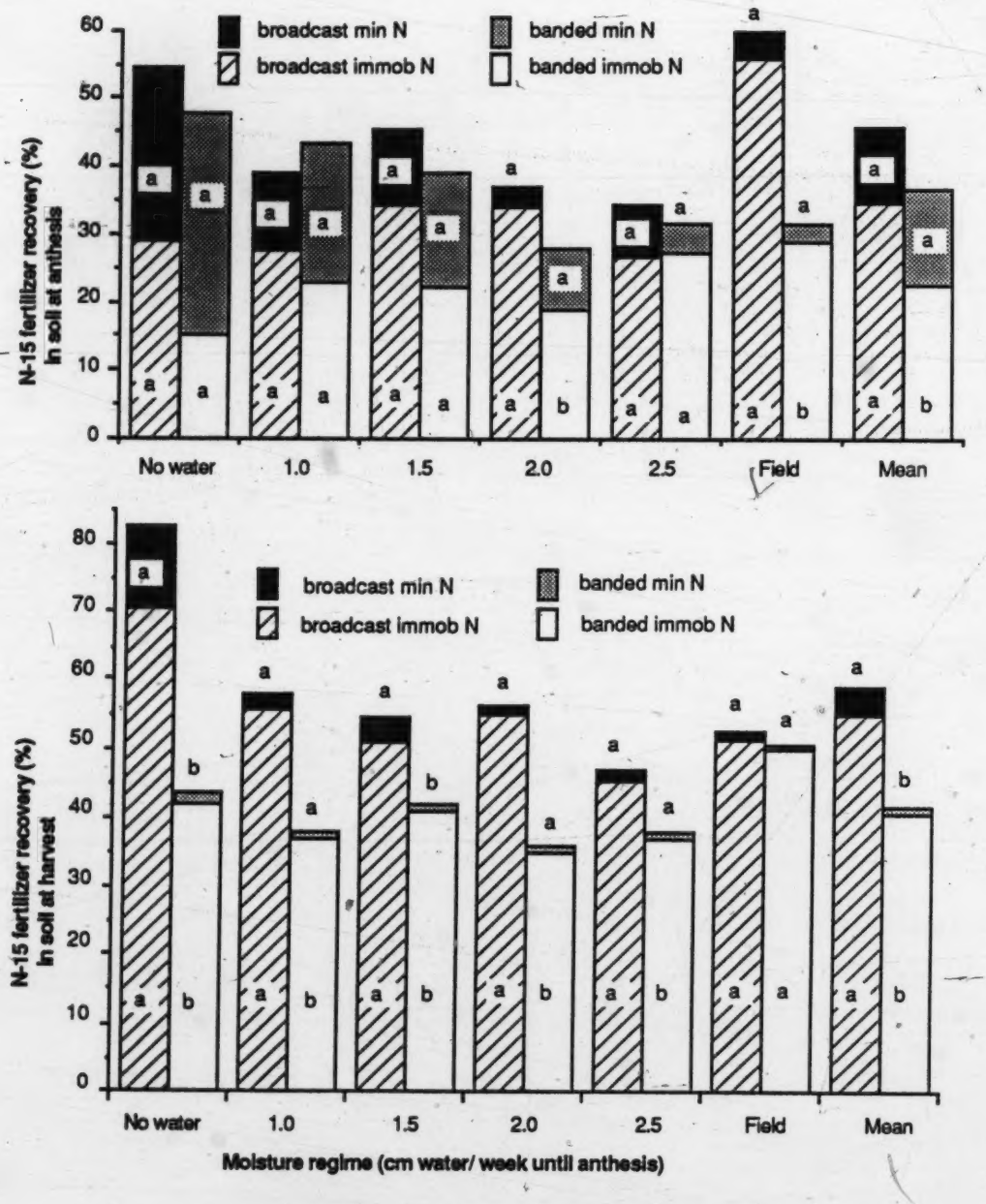

Figure 8. Effect of placement on % fertilizer recovery as mineral N or immobilized N in the total soil depth at anthesis and harvest

There is no significant difference at the 5% level between placements under the same moisture for the same N component when followed by the same letter

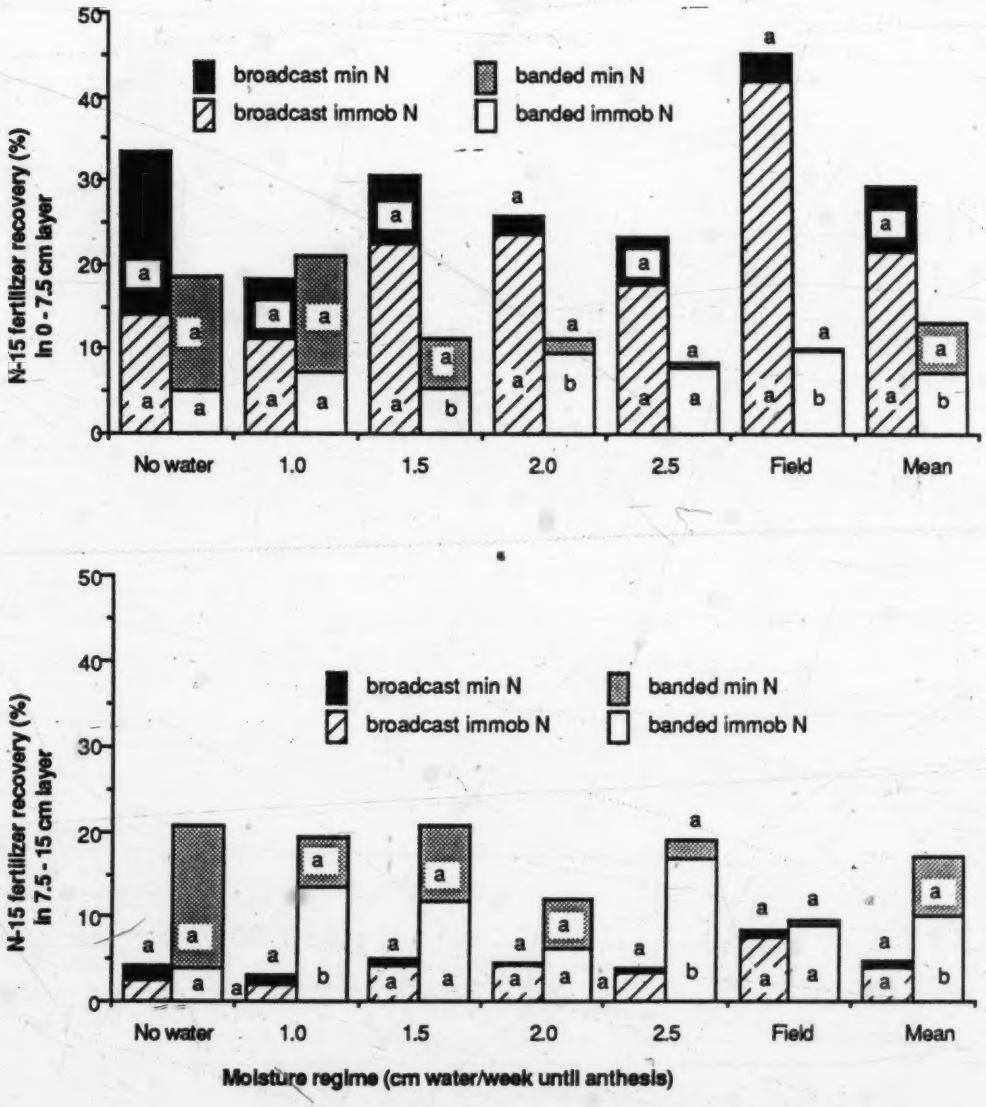

Figure 9. Effect of placement on % fertilizer recovery as mineral N or immobilized N in the 0-7.5 and 7.5-15cm soil depth at anthesis

There is no significant difference at the 5% level between placements under the same moisture and in the same N component when followed by the same letter

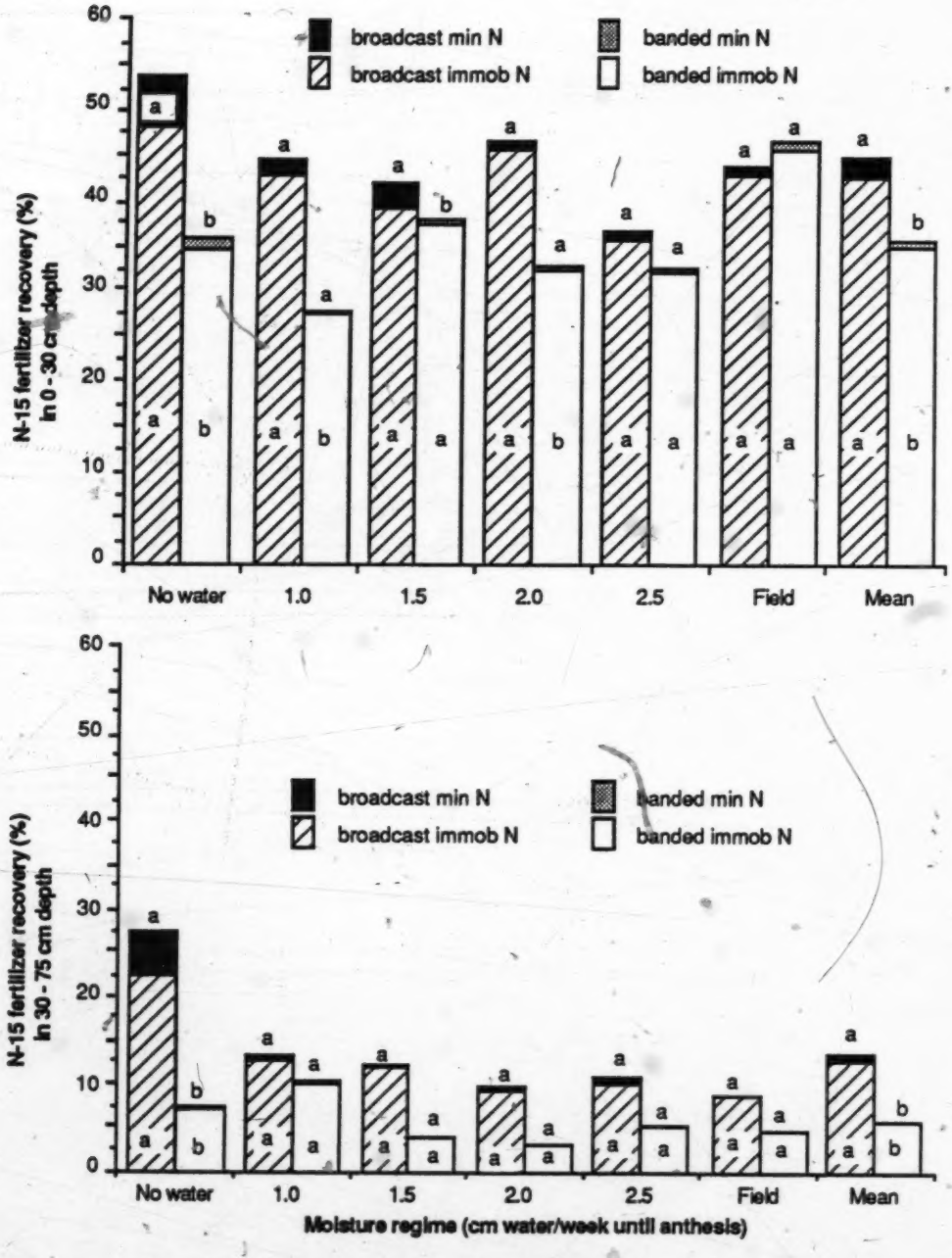

Figure 10. Effect of placement on the % fertilizer recovery as mineral N or immobilized N in the 0-30 and 30-75 cm depth at harvest

There is no significant difference at the 5% level between placements under the same moisture for the same N component when followed by the same letter

Most of the fertilizer N recovered in this soil layer occurred as immobilized N (three quarters and one half of the residual N with BI and DB respectively). Large placement differences were evident; on average, BI experienced greater immobilization of fertilizer N than DB (22 and 8% of the applied fertilizer respectively). The placement-water interaction was not significant. The level of moisture significantly affected the amount of immobilization; the Field moisture treatment exhibits the highest and there tends to be less immobilization with less water.

In the 0-7.5 cm layer, placement did not significantly affect the amount of fertilizer N left as inorganic N. The significant effect of water shows that more fertilizer remained as mineral N with lower weekly watering rates. The placement-water interaction was not significant (Appendix 3a).

7.5-15 cm depth

At anthesis (Figure 9), DB left more fertilizer N in the 7.5-15 cm layer, on average, than did BI (17 vs 5% of the applied fertilizer respectively). When comparing placements under the same moisture regime, the significant differences occur at low moistures (No water and 1.0 cm water). The interaction between placement and water, and the main effect of water were not statistically significant.

A large proportion of the fertilizer N remaining in this soil layer at anthesis was bound in organic forms (two thirds to three quarters). Significantly more immobilized N was detected with DB than BI when averaged over the moisture regimes (10 vs 4% of the fertilizer applied respectively). Placement comparisons under the same water level revealed statistical differences only under 1.0 cm and 2.5 cm water / week . The main effect of water and the interaction with placement were not significant at this depth.

No statistical differences were found in amounts of fertilizer mineral N in this layer at anthesis. DB tended ($P \leq .06$) to have more fertilizer mineral N than BI, on average. The main effect of moisture and the water-placement interaction were not significant .

15-30 cm depth

There were no statistical differences (see Appendices 3a and 7) in this depth at anthesis among placements or moisture regimes with regard to residual fertilizer N, immobilized or fertilizer mineral N. Approximately 4 - 5% of the fertilizer applied was recovered in this layer at anthesis, three quarters of which was in organic forms.

30-60 cm depth

At anthesis, differences in the amounts of residual fertilizer N and immobilized N were not significant at this depth (see Appendices 3a and 7). There was a trend ($P \leq .06$) of more immobilized N with BI than DB. Also, there tended ($P \leq .06$) to be more residual fertilizer N in this soil layer with BI and with drier regimes. About 4 - 5% of the fertilizer application was recovered in this layer, three quarters of which was immobilized N. There was significantly more fertilizer mineral N present under the low moisture regimes, and it tended ($P \leq .09$) to be higher under BI.

4. Soil + plant fertilizer recoveries at anthesis

Averaging over the moisture regimes at anthesis (Figure 11), DB resulted in significantly greater fertilizer recovery in the plant + soil system than BI (104 vs 78 % of the applied fertilizer respectively). Comparing placements under the same water levels, a significant difference (Appendix 3a) occurred among placements only under the No water regime. The interaction and main effect of water were not significant. A significant replicate effect existed.

5. Soil + plant fertilizer recoveries at harvest

A significantly (Appendix 3a) higher fertilizer recovery in the plant + soil system (Figure 10) was realized under DB than BI at harvest (109 vs 98 % of the applied N respectively, on average). The significant interaction term (Appenidx 3a) indicates that the magnitude of the DB superiority varied with moisture level. The greatest difference occurred under the Field moisture regime where an unusually high fertilizer recovery (%) was calculated under the DB placement (spurious result?). The main effect of water was not significant. The fertilizer % recoveries

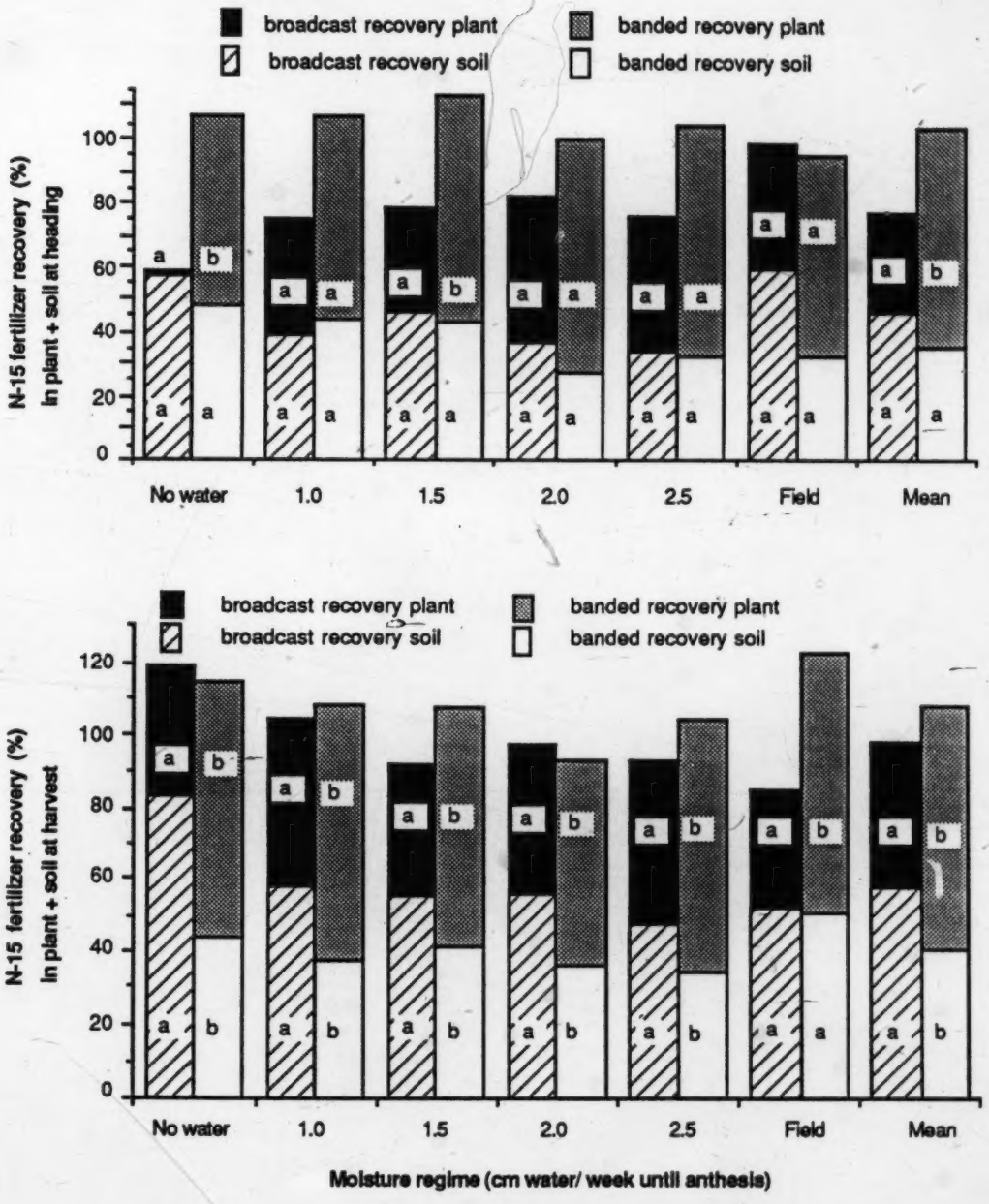

Figure 11. Effect of placement on plant and soil fertilizer recoveries at anthesis and harvest

There is no significant difference at the 5% level between placements under the same moisture and for the same plant or soil component when followed by the same letter.

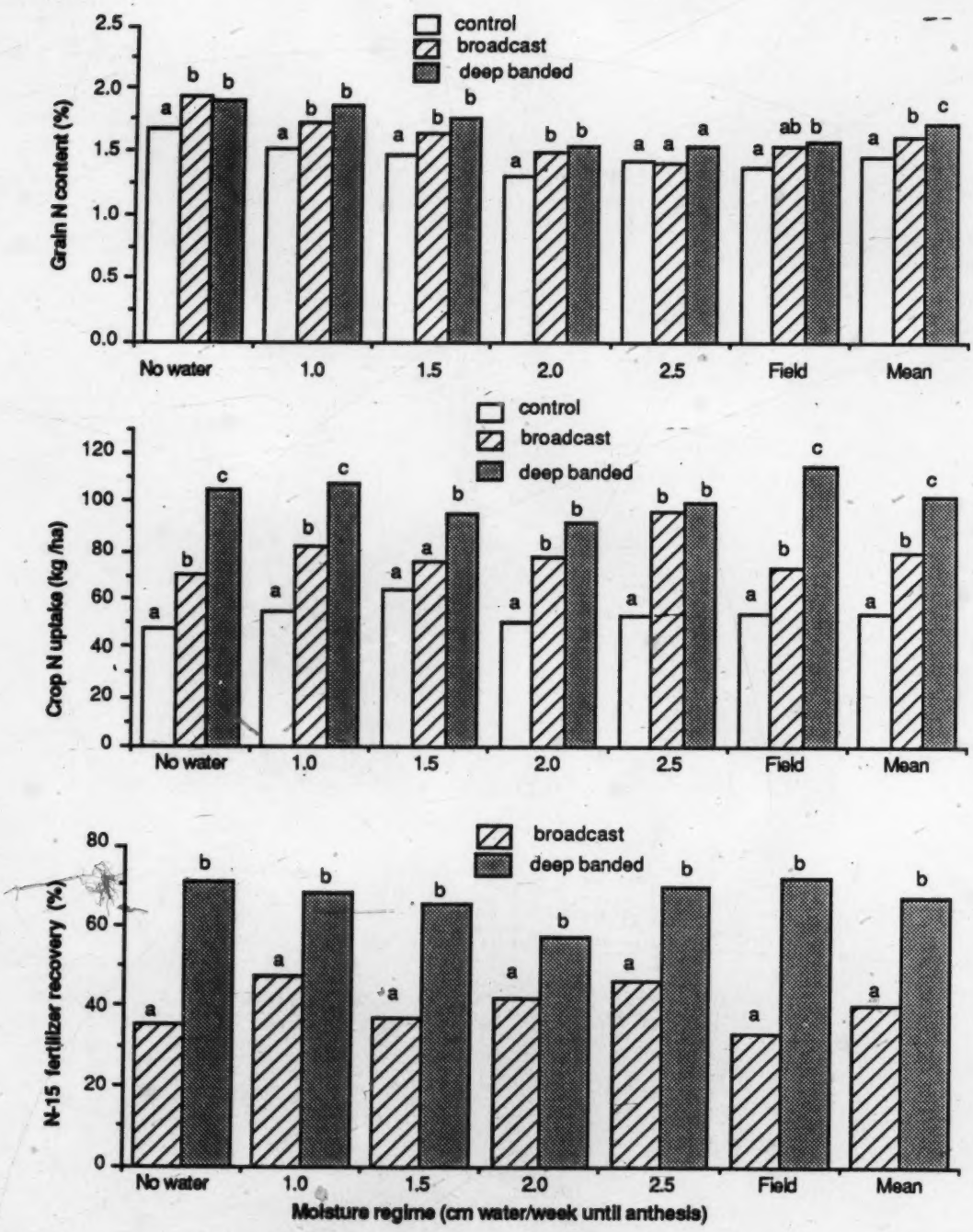

Figure 12. Effect of placement on grain % N, crop N uptakes and % fertilizer recovery at harvest

Columns in the same moisture regime followed by the same letter are not significantly different at the 5% level.

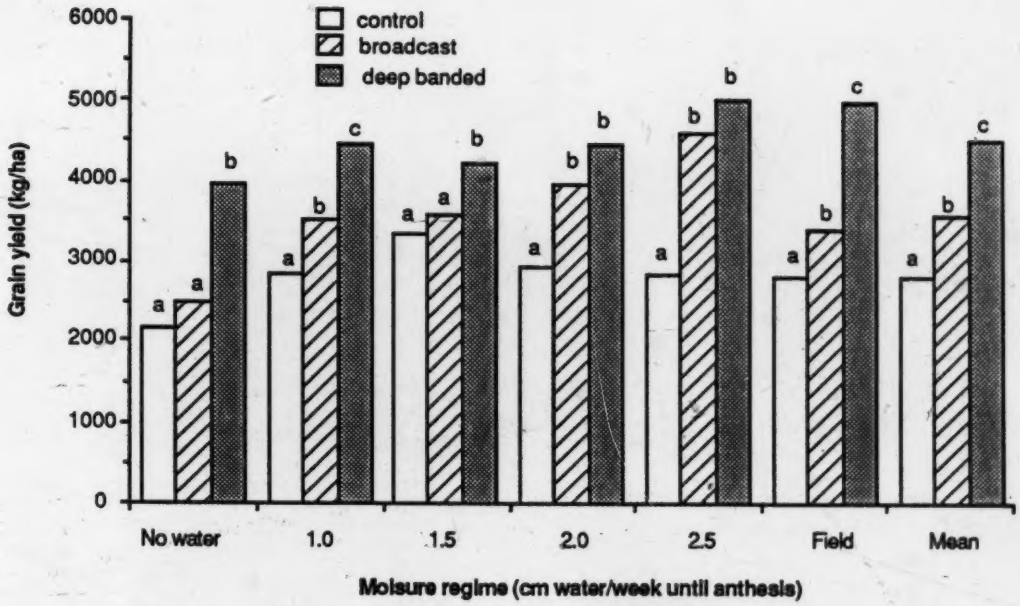

Figure 13. Grain yields of fertilizer placements and control under incremental moisture regimes

Columns in the same moisture regime having the same letter are not statistically significant at the 5% level

appear to have increased from anthesis to harvest, mainly due to higher recoveries in the soil at the latter sampling date.

6. Harvest data

Averaging over all the moisture regimes, DB produced significantly higher N content (%) in the grain (Figure 12) than did BI and both were statistically different from the CON (1.71, 1.63 and 1.46 % N respectively). Comparing subplots within the same moisture levels shows no significant differences. Although the main effect of water was not significant, there was a trend ($P \leq .06$) to higher N content (%) in the grain with less water. The interaction between fertilizer subplots and moisture was not significant.

On average, DB resulted in significantly greater crop N uptake (Figure 12) than BI and both were significantly better than CON (102, 79 and 54 kg / ha respectively). Although the interaction with moisture was not significant, there was a tendency ($P \leq .07$) for the largest differences to occur under drier regimes. The effect of water was not significant.

The data presented in Figure 13 demonstrates the effects of nitrogen and its placement on the economic component of the crop -- grain yield. DB produced significantly greater grain yields than BI on average, and both were significantly better than the CON (4515, 3581 and 2825 kg grain / ha respectively). The significant interaction with moisture (Appendix 3a) reveals a change in the magnitude of placement differences depending on moisture level. Under drier regimes (includes Field) DB yielded more than did BI which was not significantly different from the CON. With wetter regimes, DB and BI yielded the same and both were better than the CON. Notably the highest grain yields were obtained with DB and BI under the highest watering schedule and under natural precipitation. The main effect of water was not significant.

The higher yields under DB was achieved in spite of fewer plants per square meter due to a germination problem associated with that treatment (Appendix 5). The yield increases of both DB and BI were due to significantly higher head numbers and

head sizes (Appendices 3a and 5). Head size also increased with the level of irrigation per week.

On average, DB plants recovered more fertilizer at harvest than did BI (67 vs 40% of the application respectively, Figure 12). The main effect of water was not significant, nor was its interaction with placement.

7. Placement effects on soil fertilizer recovery at harvest

Total soil depth (0-90cm)

Averaged over the moisture levels at harvest (Figure 11) , BI resulted in significantly more fertilizer remaining in the soil than with DB (58 vs 42 % of the applied N respectively). A significant interaction with moisture (Appendix 3a) indicates that the difference between placements varied with the water level. The greatest differences occurred under No water regime (82 vs 44 % recoveries for BI and DB respectively), but significant differences existed for other regimes except for Field. The main effect of water was not significant.

The biggest proportion of the soil residual fertilizer N at harvest was in organic forms ; as much as 71 % of the fertilizer applied was immobilized (Figure 8). Over all the moisture regimes, BI experienced greater immobilization than DB (55 vs 40 % of the application respectively). A significant interaction with moisture (Appendix 3a) shows that the largest difference between placements happened under No water regime (71 and 42 % immobilization of the applied N for BI and DB respectively). The least amount of immobilization occurred at 2.5 cm water / week, but was still appreciable (BI 46 %; DB 34%). Under the Field regime, the placements were statistically similar. A significant water effect was lacking.

The amounts of fertilizer N remaining at harvest in mineral form was much less than immobilized N (just 2% of the application on average). Averaging over the moisture regimes, BI resulted in more residual fertilizer inorganic N than DB in the total soil depth at harvest (3.4 vs 1.0 % of the applied N respectively, Appendix 8). The significant interaction with moisture (Appendix 3a) reveals that the greatest differences between placements occurs under drier regimes, especially No water (BI

12%; DB 2%). The significant main effect of water also shows that more residual fertilizer mineral N was left under the No water regime than any other moisture level. There was a significant replicate effect on residual fertilizer mineral N.

0-30 cm depth

Significantly more fertilizer N remained in this soil depth (Figure 10) under BI than with DB, on average, at harvest (45 vs 36 % of the application respectively). A significant interaction with moisture (Appendix 3a) indicates that the degree of difference among placements varied with the water level. Statistical differences between BI and DB exist at drier regimes only. The main effect of water was not significant. The major portion of the residual fertilizer was located in this layer.

Immobilized N represents the largest fraction of the residual fertilizer. Significant immobilization differences between placements occurs at low moistures only, which reflects a significant interaction with moisture. The main effect of water was not significant.

In contrast, there was a significant effect of water on residual fertilizer mineral N in this depth at harvest. The No water regime left significantly more fertilizer in mineral form than any other moisture regime. Averaging over the water levels, BI resulted in significantly greater quantities of fertilizer mineral N remaining than did DB (2 vs 1% respectively). However the magnitude of the residual fertilizer mineral N is small compared to the immobilized fertilizer N. A significant interaction with moisture (Appendix 3a) reveals that significant differences between placements occurred only at low moistures.

30-75 cm depth

Averaging over all the moisture levels at harvest, significantly more fertilizer was left in this soil layer (Figure 9) by BI than DB (13.5 vs 5.7 % of the applied N respectively). Comparing placements under the same water levels, significant differences existed only with No-water. The interaction term was not significant. The main effect of water was not significant, but a trend ($P \leq .08$) of greater residual fertilizer

N with drier regimes is apparent. An appreciable amount of fertilizer N was recovered in this layer , as much as 27.5 % of the application.

Immobilized N represents the biggest proportion of the residual fertilizer N at this depth. Averaged over the moisture regimes, significantly more immobilization occurred under BI than DB (12.5 vs 5.6 % of the applied N respectively). Comparing placements under the same moisture levels shows that a significant immobilization difference happened only under the No water regime. The interaction between moisture and placement with respect to immobilization was not significant. The main effect of water was not significant.

In contrast, water significantly influenced the amounts of fertilizer mineral N remaining in this depth at harvest. The No water regime left significantly greater quantities of fertilizer mineral N than any other moisture level. Averaging over the moisture levels, BI resulted in more residual fertilizer as mineral N than did DB (1.0 vs 0.1 % of the application respectively). The magnitude of residual fertilizer as mineral N at this depth is tiny compared to immobilization. The difference between placements was significant only under the No water regime, as reflected by the significant interaction term.

75-90 cm depth

Significantly more fertilizer mineral N was found in this soil layer at harvest under No water than any other moisture regime (see Appendix 8). BI also was associated with higher fertilizer mineral N than DB . The recovery of fertilizer as mineral N at this depth is not important in absolute amounts but is an indication of relative leaching losses.

V. DISCUSSION

1. Usefulness of rain shelters

The purpose of this experiment was to assess the effect of moisture on fertilizer uptake efficiency of deep banded vs broadcast-incorporated placements. Although the environmental conditions could have been more conveniently and accurately controlled with greenhouse techniques, the author felt that the soil volume restrictions of a pot would not simulate field situations. Therefore the use of field rain shelters was chosen.

The design and construction of the rain shelters was basic; sophisticated materials and technology were not used. This resulted in substantial cost reductions -- the cost for the shelters approached just $3, 000. However, the carpentry skills and labor of the author are not considered in this cost. The construction involved two solid weeks of work. The watering technique of hand application from sprayer tank-tractor was also labor intensive. Finally, the hand seeding and fertilization of all the plots was hard tedious work, to be blunt. Again, this has not been considered in the cost of the shelter experiment. In the author's opinion, if all the skilled and manual labor were accounted for, and more sophisticated greenhouse materials used, the cost of the shelters would have been prohibitive.

Now to address the important question -- did the shelters work ? The comparison of sheltered plots to the uncovered field plots (natural precipitation) supplied useful information. Approximately 225 mm of rain fell over the growing season (Appendix 4) at Ellerslie in 1986, resulting in very good crop yields in the area. The grain yield of the field plot (3720 kg / ha) corresponds to the wetter half of the controlled moisture regimes (in between the 1.5 and 2.0 cm water / week). The 2.0 cm water regime received 120 mm of irrigation plus 104 mm precipitation after anthesis (July 14) for a total of 224 mm, which matches the field's precipitation total. However, the temperatures recorded in the shelters were 8° C higher on average than the maximum daytime air temperature. This temperature rise decreased the soil storage of the irrigation (more evapotranspiration) as was revealed in the lower soil

moisture contents at anthesis. The warmer microclimate under the shelters induced a noticeably taller crop which matured about one week earlier than the field plot. The general shape of the N content , N uptake and fertilizer recovery curves resemble those from moderate moisture regimes. Therefore, the rain shelters did not alter the climate enough to drastically change plant fertilizer uptake characteristics and the data produced by this experiment should be generally valid.

Improvements to the design of the shelters could help alleviate the temperature increase and thus more closely mimic the outside environment. Removable sides, rooves or both would improve ventilation (but also require more labor). Spacing the shelters farther apart would also help. One observed benefit of the enclosures was a noticeable reduction in barley scald (*Rhynchosporium secalis*) compared to the field plots.

2. Weekly patterns of N fertilizer utilization

The data presented in Figure 1 - 7 demonstrate a clear superiority of DB over BI in N fertilizer utilization under every moisture regime. There was a significantly higher fertilizer recovery with DB right from the first sample week (two leaf stage or about three weeks after seeding). The banding benefit continued to increase over the sampling period. A dramatic difference between the two placements occurred under the No water regime where BI plants recovered little of the fertilizer (1 - 2 %) until the moisture stress was removed at anthesis. This agrees with observations that BI plants were noticeably paler green, with more firing of the lower leaves at anthesis. Under the No water regime, the most striking differences occurred, and the DB plants possessed much larger, wider, darker green leaves and larger heads. This low fertilizer recovery under No water strongly supports the concept of stranding. As more water was applied, the difference between the placements narrowed, suggesting that stranding was diminishing. However, a significant difference in fertilizer recovery still existed at higher moistures which may be attributed to greater losses under BI by immobilization (predominantly), denitrification and leaching. The DB fertilizer recovery appeared relatively unaffected by water regime compared to

the great response of BI. DB seems to buffer the effects of moisture and thus should be regarded as a valuable management practice to lessen the impacts of drought. Both placements tended to reach a plateau of fertilizer recovery at the fourth (heading) or fifth (anthesis) sample weeks. This suggests that the available forms of the N fertilizer were largely utilized by this stage and that root absorption has greatly decreased (McNeal *et al* 1966, Boatwright and Haas 1961). Plant loss of gaseous N could also have occurred during anthesis and grain filling.

The higher fertilizer recovery in DB plants compared to BI is reflected in significantly greater N uptakes and N content in the plants over the season. The significantly better crop N uptakes and plant N content with the fertilizer treatments under higher moisture regimes at later sample weeks confirms that Ellerslie was a N responsive site.

Although the N content tended to differ from the first sample week, crop N uptakes did not significantly diverge until the second or third sample week. At earlier stages of growth, the N status is important for reasons other than dry matter production and crop N uptake. Potential number of fertile tillers (and therefore heads) and number of spikelets (head size) are determined at this time (Goh and Haynes 1986). Thus the limits of the potential grain yield is set very early in response to N status and also moisture conditions (Day *et al* 1978, Lawlor *et al* 1981). Although DB resulted in noticeably more and larger heads at harvest (Appendix 5) there was a confounding influence of lower plant densities under this treatment. This reduction in plant densities under DB resulted from poorer germination which was attributed to accelerated drying of the loosened soil in the band under the seed row. In the author's opinion, the greater number of heads and head size under DB compared to BI and CON is probably due to a more favorable N status early and throughout the growing season, as shown by the N content data, rather than an influence of lower plant density. The author believes that DB allows for higher yields partly because the increased early access to fertilizer sets a higher yield potential.

By the third sample week, significant N uptake and N content differences among the fertilizer subplots were evident, mainly under the drier moisture regimes. This pattern was maintained through to harvest. The greater amounts of soil N taken up by the crop with DB correspond to the better recovery of fertilizer from the band, resulting in both higher dry weights and N content. Previous research (Boatwright and Haas 1961, McNeal *et al* 1966) has shown a strong relation between the grain N content and yield with the quantity of N in the top growth because of N translocation from senescing leaves and stems to the developing grain. Therefore part of the DB benefit lies in improving the N status of the foliage and subsequently providing a greater N reservoir (source size) for grain filling.

At anthesis , if one subtracts the control N uptake from that of DB, an average difference of 50 kg N / ha is obtained. However, since the average DB fertilizer recovery is 67 % of the application, or 34 kg N / ha, an increased uptake of indigenous soil N (16 kg N / ha) is realized with DB, but not with BI. At harvest, DB maintained the increased indigenous soil uptake of 15 kg / ha, and BI had 5 kg / ha. This may be due to the 'priming effect' where N additions stimulate mineralization of recalcitrant soil organic matter, or it may be a result of an increased volume of soil explored due to root proliferation , and deeper root penetration. The former explanation does not appear valid because BI should have induced more mineralization due to greater fertilizer contact with soil, and thus should have realized a increased uptake of indigenous soil N. Therefore, the priming effect appears to be due to larger soil volumes explored.

Unlike the fertilizer recovery curves, the N uptake curves have not generally reached a plateau by anthesis, which suggests that root N absorption continues during grain filling, but at a reduced rate. Also, the dominance of available fertilizer N has diminished greatly by this time leaving mainly indigenous soil N for absorption. However at drier regimes, a plateau of N uptake was reached prior to anthesis by both BI and CON due to depletion of positionally available N . Notice that under the No water regime, the BI and CON are similar in N uptake and N content curves, which

supports the idea of stranding with BI. Approximately 60 kg N / ha appeared to be the indigenous soil supply of available N until anthesis.

Although the main effect of water on N uptake and N content was not significant, the trend to higher N content and uptake with more water applied largely reflects the improved fertilizer access with better moisture. Undoubtedly some of this increased uptake is also due to improved root growth under better water conditions causing a larger soil volume to be utilized and greater mass flow plus diffusion of dissolved ions to the root (Viets, 1972).

The decline of the N content in plant material over the season results mainly from increasing proportions of senescing leaves which have experienced nutrient remobilization to younger growing tissue. This trend is consistent with the findings of others (Boatwright and Haas 1961, McNeal *et al* 1968).

3. Residual fertilizer in the soil

The purpose of the soil sampling in this experiment was to compare the effect of fertilizer placement on the amounts of residual fertilizer , immobilization and stranding at anthesis and harvest. Significant differences did exist between the placements with the soil data, but generally these data were much less sensitive than the plant data in detecting differences. This lower sensitivity can be attributed to two factors : a great variability in soil fertilizer N distribution, and an imprecise sampling technique for the DB treatment. Due to the disproportionate contribution of soil from the band in the sample, the amounts of N fertilizer recovered as mineral or immobilized N will be overestimated, resulting in underestimation of true differences between the placements. In the following discussion, one must bear in mind that noted trends may indeed have been significant differences if more representative samples had been obtained. In hindsight, the author recognizes that certain modifications to the experimental design and technique would improve the precision of the treatment comparisons. To estimate more accurately the true treatment means, more replication would be necessary. This could be achieved by decreasing the number of water regimes, which appeared to be set in finer increments than justified

by the variability of soil and plant data. Secondly, the individual plots could be sectioned into separate sample areas to allow for destructive soil slice sampling without affecting the water infiltration, fertilizer movement and plant uptake patterns on the remainder of the plot. Perhaps it would then be necessary to increase the plot size. Evaluation of such experimental limitations and their influence of the precision of the data comprised an important aspect of this learning experience.

A. Stranding

The soil data at anthesis did not consistently support the concept that stranding occurs with BI under dry moisture regimes. This is surprising in view of the dramatic differences in fertilizer recovery by the plant as discussed earlier. Figure 7 shows that no real differences between placements with regard to residual fertilizer mineral N were detected in the 0 - 7.5 cm layer. The significantly greater amounts of fertilizer mineral N remaining in the top soil layer with the drier regimes shows that less absorption and leaching deeper into the root zone occurred. The net upward movement of water through the soil due to sustained evaporation promoted the concentration of fertilizer in the surface soil zone. Thus even DB placed fertilizer was in the top 7.5 cm in significant amounts under the No water and 1.0 cm regimes. DB resulted in more fertilizer N in the 7.5-15 cm depth at anthesis, which is in a more favorable zone for plant uptake due to generally higher moisture contents.

However, the author has reason to suspect error in the BI mineral N data in the 0 - 7.5 cm layer at anthesis. Firstly, the negligible fertilizer recovery in the plant at anthesis under the BI No treatment combination suggests that the fertilizer was not utilized and either remained in the soil as urea + mineral N + immobilized N or was lost due to volatilization, denitrification and leaching. The latter two are unlikely under the dry conditions imposed. Volatilization can be ruled out since all of the fertilizer was recovered in the plant + soil system at harvest (Figure 11). In fact, an increase in soil residual fertilizer N was measured from anthesis to harvest -- BI 37 to 58 %; DB 36 to 41 % of the application. The DB increase in soil fertilizer recovery is within experimental error, but the BI increase was not. The apparent increase in soil

fertilizer recovery from anthesis to harvest was most pronounced under BI dry regimes ; for example, BI-No-water combination showed an increase from 57 % to 82 % recovery of the applied N . This causes an obvious speculation that fertilizer urea + mineral N was underestimated in the top 0 - 7.5 layer at anthesis, especially with BI. This may have occurred due to nonrepresentative soil sampling -- the dry surface peds which feasibly contained fertilizer (concentrated there due to evaporation) were prone to falling out of the soil corer during its removal from the hole. Hindsight again suggests that a more representative sample could have been obtained with removal of a block volume of surface soil. In brief, the soil fertilizer mineral N data at anthesis does not provide support for the stranding concept, but due to the inconsistencies in the data,one cannot conclusively discount the possibility that stranding occurred.

In contrast, harvest soil data (Figure 9) indicate that significantly more residual fertilizer mineral N remained in the 0 - 30 cm depth under BI than DB, especially with the No water regime (7 and 2 % of the applied N respectively). The strong interaction of placement with water at this depth indicates that the differences between placements in fertilizer mineral N recovery were dependent on moisture level. In addition, 5 % of the fertilizer applied was found in the 30 -75 cm depth at harvest under the BI - No water combination which was significantly greater than under DB (0.2 %). This residual fertilizer mineral N at deeper depths at harvest probably occurred as a result of leaching from the surface zone after removal of shelter rooves. The sum of these two depths for BI under the No water regime shows that 12 % of the fertilizer application remained in mineral N form at harvest, compared to just 2 % for the DB (Figure 8). The above evidence and the weekly plant fertilizer recoveries indicate that stranding indeed occurred under the dry regimes, and further confirms the spurious nature of the soil results at anthesis. Thus the author concludes that stranding of BI fertilizer is a real concern under dry moisture situations, and leads to poor fertilizer utilization, plant growth and grain yields. This agrees with the conclusions of others (Chaudhary and Prihar 1974, Sharma and Chaudhary 1983,

Bole *et al* 1984, Carter and Rennie 1984, Kucey 1986, Harapiak *et al* 1982, Harapiak and Penney 1984).

B. Immobilization

The soil fertilizer recovery data at both anthesis and harvest reveals that immobilization plays a big role in fertilizer efficiency. When averaged over all the water levels at anthesis, BI experienced significantly more immobilization of the fertilizer N than DB (35 vs 23 % of the applied N respectively). By harvest the magnitude of immobilization increased and the difference between placements had widened (with BI 55 % and DB 40 % of the fertilizer was immobilized). Most of the fertilizer N immobilization occurred in the surface layer, as shown in Figure 8 and 10. This is attributed to addition of the fertilizer to the zone of highest microbe numbers and activity.

Besides magnitude, there is one important difference between the harvest and anthesis fertilizer immobilization. At anthesis, there was a trend to more immobilization with greater amounts of water applied per week, while the reverse was true at harvest. Immobilization differences between placements were largest with wetter regimes (includes Field) at anthesis, but with drier regimes at harvest. This can be interpreted as follows. Up to anthesis, microbial activity , like plant growth would be limited by moisture . Therefore one could expect more immobilization with higher moisture levels . Upon removal of shelter rooves and with subsequent precipitation, microbial activity would resume in dry regimes. The glut of unused fertilizer N in the dry regime plots would then be available for assimilation. Since root nutrient absorption largely declines after anthesis (McNeal *et al* 1966, Boatwright and Haas 1961) , most of the residual fertilizer N would thus be subject to immobilization. In contrast, less fertilizer N was present in available forms under wetter regimes due to plant and microbe utilization during the early growth stages, leaving less for immobilization from anthesis on. The end result is greater immobilization at harvest under early dry situations than wet . Immobilization clearly depends to a large degree on the extent of stranding early in the season.

More immobilization is experienced under BI than DB at both sample dates because of increased soil and therefore microbial contact with the fertilizer. Also, there may be temporary toxic effects on microbes due to high fertilizer salt and NH_4^+ concentration in the band. The relatively deep band placement helps to avoid the biologically active surface layer. Banding enabled increased N uptake early in the season as shown by the weekly fertilizer recoveries and thus reduces the exposure time of fertilizer to assimilating microbes.

Immobilization accounts for a large portion of the fertilizer fate, even with DB. Averaged over all the moisture levels and placements, 48 % of the fertilizer was immobilized, which agrees with the findings of Malhi and Nyborg (1983). It is tempting to compare the magnitude of stranding and immobilization at harvest and conclude that the former is insignificant. However the results and discussion above demonstrate that the degree of immobilization is influenced by the extent of stranding early in the growing season. The two are thus very interrelated.

C. Effects of placement on other soil processes

The 75 - 90 cm depth at harvest was included to indicate leaching. If fertilizer mineral N was detected at this depth, leaching was assumed to have occurred. Only relative amounts of leaching could be inferred from the amount of fertilizer recovery in this soil layer.

Significantly more leaching occurred under No water than the other moisture regimes due to substantial rain after the removal of the shelter rooves. The abundant mineral N at this time in the surface soil was evidently very susceptible to downward translocation with percolating water, probably through large cracks which were prevalent in the dry profile. BI experienced relatively greater leaching losses than DB, especially under early dry situations. This is attributed to greater amounts of fertilizer mineral N remaining at anthesis. Less leaching occurred under wetter regimes since the fertilizer was largely assimilated by plants or microbes .

Since many of the plant + soil fertilizer recoveries at harvest were close to 100 % or more (the lowest was 85 % with a LSD of 16.6 %), one can infer that the

processes of denitrification and or volatilization did not operate to a measurable extent in this experiment. Also, the lack of significant differences between placements in soil water contents at anthesis suggests that there was no effect of placement on soil water use or that the sampling technique was not sensitive enough to detect differences.

4. Yields

Any discussion of the significance of fertilizer efficiency would be incomplete if the treatments effects were not related to the economic product -- grain.

Averaging over all the experiment, DB produced significantly more grain than BI, and both were better than the control (4515, 3581 and 2825 kg grain / ha respectively, Figure 13). The significant placement interaction with moisture indicates that the largest banding benefit over BI occurs under dry regimes. Under No water, DB produced 3981 kg grain / ha, while the BI was not statistically better than the CON (2488 and 2142 kg / ha respectively). The weekly fertilizer recovery and soil residual fertilizer data suggest that stranding limits the early growth on the BI plot, adversely lowering the N status of the plant and reducing the yield potential (number and size of heads). Then as the moisture stress was removed at anthesis, the majority of the stranded mineral N became immobilized, partly because root absorption capacity greatly decreases past heading. The end result on the plant was a smaller N reservoir in the dry matter (leaves plus stems) from which nutrient remobilization occurs during grain filling. Lower yield was the inevitable consequence of N deficiencies suffered early in the season.

With higher watering regimes, the yield difference between placements became statistically insignificant, although DB tended to produce more grain. This narrowing of the yield difference can be attributed to the absence of stranding under better moisture conditions. Thus any yield disparities would be due to immobilization differences. Although BI resulted in significantly more immobilization under the wet regimes at harvest (except for Field), this did not translate to a statistical yield difference.

In summary, the source of the DB yield benefit arises from reduced stranding under early season droughts, and less immobilization under all moisture regimes. This allows for greater N absorption by the crop, raising the N status and thereby creating a higher yield potential in the early stages of growth. The larger N reservoir (higher % N and dry matter weights) with DB in later growth (post anthesis) allows for greater nutrient remobilization into developing grain, thus helping to realize the higher yield potential set earlier. The difference in utilization of fertilizer between placement methods causes a divergence in the fertilizer fates. With DB the majority (67%) of the fertilizer was recovered by the crop whereas roughly the same proportion (60%) of the fertilizer was left in the soil under BI.

The greatest grain yield occurred under the wettest regime, but there was not a drastic yield reduction with DB under moisture stress as exhibited by BI. This demonstrates the ability of DB placement to buffer the effects of drought..

Finally, an economic assessment of the effect of fertilizer placement reveals that higher margins were realized with DB than BI. Given current prices for urea (46-0-0) of $240 / tonne (March, 1987), the cost of N fertilizer was $26 / ha. An evaluation of P fertilizer effects is not possible since all plots received a blanket application. Current street prices for barley are approximately $75 per tonne. No consideration is made for grade differences -- shrivelled kernels with lower N contents under CON and BI in dry regimes would lower their value. A simple economic balance sheet for the effect of fertilization and placement over the entire experiment is as follows:

Cost or revenue	CON	BI	DB
		$ / ha	
Fertilizer cost	---	26.00	26.00
Application cost	---	5.00	10.00
Grain revenue	211.88	268.58	338.63
Revenue due to fertilizer	---	56.68	126.75
Fertilization margins	---	25.68	90.75
DB benefit over BI	---	---	65.07

Notice that DB results in $65 more per ha than BI. For every dollar spent for DB N fertilizer, $3.50 was returned in grain, compared to $1.80 for BI. A 350 % return on investment was realized over this wide range of moisture conditions for DB. The fertilizer margins and banding benefits for each moisture regimes are summarized in Table 2. Note the dramatic difference in fertilization margins under drought and field conditions depending on placement ! DB maintains a high fertilization margin throughout this wide range of moisture conditions (except for 1.5 cm). In contrast, the margins of BI N fertilization relies heavily on moisture. The greatest banding benefit (in dollars) happens under unfavorable early season moisture situations. This reinforces the notion that DB placement is a valuable management tool to buffer the adverse impacts of drought. Given the discouraging economic climate facing most prairie farmers, they can ill afford to ignore the greater margins realized with fertilizer placement technology.

Table 2. Fertilization margins and the banding benefit

MOISTURE REGIME	FERTILIZER PLACEMENT	FERTILIZATION MARGINS	BANDING BENEFIT
		----------$ / ha	----------
No water	BI	[5.03]	
	DB	101.93	106.96
1.0 cm / wk	BI	18.65	
	DB	84.92	66.27
1.5 cm / wk	BI	[13.55]	
	DB	30.35	43.90
2.0 cm / wk	BI	45.41	
	DB	80.24	34.83
2.5 cm / wk	BI	98.62	
	DB	124.22	25.60
Field (nat. ppt)	BI	10.39	
	DB	123.09	112.70

VI . CONCLUSIONS

The data generated with this fertilizer placement experiment under controlled moisture conditions lead to a number of conclusions.

(1) The crude rain shelters were a valuable research tool to assess fertilizer placement effects under various moisture regimes. Their use diminishes the need for several years of data. Yields and uptake patterns under natural precipitation were similar to the rain shelter with a corresponding equal amount of water. The higher temperatures experienced in the enclosures did not appear to drastically alter plant characteristics, but did lower soil moisture contents more rapidly. The shelters could be redesigned to more closely represent the outside environment, by improving the ventilation.

(2) The weekly patterns of N uptake and fertilizer recovery demonstrate a clear superiority of deep banding over broadcast-incorporation , especially under early dry situations. The better utilization of banded fertilizer increased plant N content, setting a higher yield potential in early growth stages, and creating a larger N reservoir to accommodate nutrient remobilization during grain filling. The strong dependence of broadcast-incorporated fertilizer recovery upon moisture suggests that stranding occurred. At higher moisture, plants under deep band placement still recovered more fertilizer, indicating that processes other than stranding were important (such as immobilization).

(3) The soil data from the anthesis sampling date do not support the interpretation of the occurrence of stranding. However, the author mistrusts the mineral N data of the 0 - 7.5 cm layer for the broadcast-incorporated treatment due to lower residual fertilizer recoveries at anthesis than harvest, especially under dry moisture regimes. The urea + mineral fertilizer N appears to have been underestimated in this soil layer at anthesis. The need for block sampling of the surface layer was evident. In contrast, the soil data obtained at harvest reveals significantly more residual fertilizer mineral N in the 0 - 30 cm depth with broadcast-incorporation, indicating that stranding indeed had taken place. The harvest soil data

and weekly plant fertilizer recoveries provide convincing evidence that stranding of fertilizer occurs with broadcast-incorporation under early dry situations.

(4) Soil fertilizer recovery data at both anthesis and harvest reveals that immobilization plays a big role in fertilizer efficiency. A large part of the improved fertilizer accessibility with deep banding is due to reduced immobilization. By harvest, broadcast-incorporation suffered 55% loss of fertilizer due to this microbial process whereas deep banding had 40% of the fertilizer immobilized. The extent of immobilization appears influenced by the degree of stranding experienced earlier in the season.

(5) Averaging over all the moisture conditions, deep banding produced significantly more grain than broadcast-incorporation (4515 vs 3581 kg / ha respectively) which resulted in a substantial margin benefit due to deep banding ($65 / ha). There was a dramatic yield difference following early dry situations -- deep banding yielded and impressive 3981 kg / ha while the broadcast-incorporation was not statistically better than the control (2488 and 2142 kg / ha). A banding benefit of $107 / ha was realized under this dry situation. The yields and margins produced by deep banding were less affected by moisture level than broadcast-incorporation . This suggests a "drought buffer" ability of deep banding placement which should be regarded as a valuable management tool to lessen the adverse impacts of drought.

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APPENDIX 1

Experimental site description

Soil : Eluviated Black Chernozem (Typic Argialboll)

Location : Ellerslie Research Station , Edmonton , Alberta. NE 1/4 Sec 24 TP 51 , R 25 , W 4.

Parent material : Lacustrine with interbedded till .

Landform and site position : Undulating , upper slope position , very gently sloping to the north-west.

Soil drainage : Well drained.

Profile description : See Crown and Greenlee (1978).

SOIL CHARACTERISTICS

DEPTH (cm)	TEXTURE	BULK DENSITY $M g m^{-3}$	pH (1:2.5 water)	ORGANIC MATTER %
0-15	SiCL	0.95	6.0	10.5
15-30	SiCL	1.05	6.1	
30-60	CL	1.30	6.2	
60-90	CL	1.45	6.0	

APPENDIX 2

N - 15 CALCULATIONS

Plant uptakes kg N / ha = (dry weight / 30 cm row) (% N) (1.667)

Plant fertilizer recovery

$$\% \text{ rec} = \frac{(\text{kg N / ha})\ (\%\ \text{abund} - .3754)\ (100\%)}{(\ 50\ \text{kg fert N / ha})\ (\ 2.4083\ \%\ \text{abund})}$$

Harvest plant and grain conversions from m row to kg / ha

$$\text{kg / ha} = \left(\frac{\text{g}}{0.2\ \text{sq m}}\right)\left(\frac{10\ 000\ \text{sq m}}{\text{ha}}\right)\left(\frac{1\ \text{kg}}{1\ 000\ \text{g}}\right)$$

Harvest fertilizer recovery in crop

$$\% \text{ rec} = \frac{[(\text{st kg N / ha})\ (\text{st \% abun} - .3754) + (\text{gr kg N / ha})\ (\text{gr \% abun} - .3773)]\ (100\%)}{(\ 50\ \text{kg fert N / ha})\ (\ 2.4083\ \%\ \text{excess})}$$

st = stubble gr = grain

Fertilizer recovery as mineral N

$$\% \text{ rec} = \frac{(\text{ ppm min N O.D. soil})\ (\text{ soil layer volume})\ (\text{Db})\ (\%\ \text{abun} - .3660)\ (100\%)}{(\ 50\ \text{kg fert N / ha}\ )\ (\ 2.4083\ \%\ \text{excess})}$$

1 ppm min N O.D. soil = 1 kg min N / 1000 M g soil

Db in M g / cubic m and soil layer volume in cubic m / ha

Fertilizer recovery in total soil N

$$\% \text{ rec} = \frac{(\ \%\ \text{N in O.D. soil})\ (\text{kg soil / ha slice}\ )\ (\ \%\ \text{abun total N} - .3682)}{(\ 50\ \text{kg fert N / ha}\ )\ (\ 2.4083\ \%\ \text{excess})}$$

Fertilizer recovery as immobilized N

% rec = % rec total soil N - % rec min N

APPENDIX 3

STATISTICAL CALCULATIONS

For comparisons with three subplots:

5% Least significant difference (LSD)

between water main plots $LSD = 2.571 \sqrt{\frac{2 \text{ (main plot error)}}{6}}$

between subplots over all $LSD = 2.179 \sqrt{\frac{2 \text{ (sub plot error)}}{12}}$

between sub plot in same water $LSD = 2.179 \sqrt{\frac{2 \text{ (sub plot error)}}{2}}$

between sub plots in different water regime

$$LSD = \text{weighted } t \sqrt{\frac{2 [\, 2 \text{ (sub plot error)} \,] + \text{main plot error}}{6}}$$

For comparisons with two placements

between water main plots $LSD = 2.571 \sqrt{\frac{\text{main plot error}}{2}}$

between placement overall $LSD = 2.447 \sqrt{\frac{\text{sub plot error}}{6}}$

between placements in same water $LSD = 2.447 \sqrt{\text{sub plot error}}$

between placements in different water

$$LSD = \text{weighted } t \sqrt{\frac{\text{sub plot error} + \text{main plot error}}{2}}$$

APPENDIX 3a F RATIOS AND THEIR SIGNIFICANCE (P)

TEST SUBJECT	REPLICATES		WATER		FERTILIZER SUBPLOTS (MAY INCLUDE CONTROL)		SUBPLOT -WATER INTERACTION	
	F	P	F	P	F	P	F	P
GRAIN % N	0.01	NS	4.52	0.06	30.48	0.00	0.97	NS
PLANT DENSITIES	3.08	NS	1.10	NS	21.26	0.00	1.82	NS
HEAD NUMBERS	0.00	NS	5.31	0.04	41.99	0.00	2.58	0.06
GRAIN PER HEAD	3.03	NS	12.86	0.01	3.24	0.08	1.13	NS
GRAIN YIELDS	2.33	NS	2.33	NS	137.60	0.00	4.08	0.01
HARVEST N UPTAKE	0.30	NS	0.44	NS	124.40	0.00	2.44	0.07
WEEK 1 N UPTAKE	2.55	NS	0.87	NS	0.82	NS	0.25	NS
WEEK 2 N UPTAKE	2.21	NS	3.37	NS	6.61	0.01	1.92	NS
WEEK 3 N UPTAKE	0.00	NS	1.01	NS	15.55	0.00	1.06	NS
WEEK 4 N UPTAKE	2.77	NS	3.70	0.09	46.51	0.00	0.86	NS
WEEK 5 N UPTAKE	10.38	0.02	2.84	NS	18.74	0.00	0.40	NS
WEEK 1 % N	4.48	0.09	4.00	0.08	9.47	0.00	0.43	NS
WEEK 2 % N	0.30	NS	0.67	NS	8.86	0.00	0.40	NS
WEEK 3 % N	3.37	NS	2.77	NS	9.91	0.00	1.03	NS
WEEK 4 % N	2.52	NS	1.89	NS	13.69	0.00	0.34	NS
WEEK 5 % N	1.64	NS	1.23	NS	14.13	0.00	0.35	NS
GRAVIMETRIC SOIL MOISTURE 0-15 CM	2.99	NS	55.38	0.00	4.58	0.03	1.52	NS
GRAVIMETRIC SOIL MOISTURE 15-30 CM	2.45	NS	33.46	0.00	0.64	NS	2.07	NS
GRAVIMETRIC SOIL MOISTURE 30-60 CM	0.04	NS	2.43	NS	0.81	NS	1.02	NS
CROP FERTILIZER % RECOVERY HARVEST	0.02	NS	0.49	NS	138.10	0.00	2.54	NS
WEEK 1 FERTILIZER % RECOVERY	2.74	NS	1.73	NS	11.93	0.01	0.14	NS
WEEK 2 FERTILIZER % RECOVERY	1.11	NS	7.54	0.02	34.28	0.00	1.09	NS
WEEK 3 FERTILIZER % RECOVERY	0.02	NS	6.59	0.03	79.83	0.00	2.12	NS
WEEK 4 FERTILIZER % RECOVERY	2.08	NS	4.06	0.08	180.10	0.00	3.08	NS
WEEK 5 FERTILIZER % RECOVERY	7.33	0.04	6.24	0.03	39.54	0.00	0.86	NS
ANTHESIS FERTILIZER REC MIN N 0-7.5	2.69	NS	10.11	0.01	0.33	NS	0.42	NS
ANTHESIS FERTILIZER REC MIN N 7.5-15	0.21	NS	0.82	NS	5.40	0.06	0.73	NS
ANTHESIS FERTILIZER REC MIN N 15-30	0.09	NS	0.87	NS	0.06	NS	1.64	NS
ANTHESIS FERTILIZER REC MIN N 30-60	0.00	NS	17.58	0.00	4.35	0.09	2.13	NS

APPENDIX 3a (cont.) F RATIOS AND THEIR SIGNIFICANCE (P)

TEST SUBJECT	REPLICATES		WATER		FERTILIZER SUBPLOTS (MAY INCLUDE CONTROL)		SUBPLOT-WATER INTERACTION	
	F	P	F	P	F	P	F	P
ANTHESIS FERTILIZER REC MIN N TOT	0.20	NS	8.60	0.02	0.41	NS	0.01	NS
ANTHESIS FERTILIZER REC IMM N 0-7.5	0.64	NS	5.82	0.04	46.48	0.00	3.69	NS
ANTHESIS FERTILIZER REC IMM N 7.5-15	0.02	NS	0.58	NS	12.38	0.01	1.59	NS
ANTHESIS FERTILIZER REC IMM N 15-30	1.22	NS	1.98	NS	0.54	NS	0.77	NS
ANTHESIS FERTILIZER REC IMM N 30-60	1.56	NS	1.75	NS	5.44	0.06	0.59	NS
ANTHESIS FERTILIZER REC IMM N TOT	0.36	NS	1.82	NS	24.77	0.00	2.56	NS
ANTHESIS FERTILIZER REC SOIL 0-7.5	9.34	0.03	7.24	0.02	15.28	0.00	1.46	NS
ANTHESIS FERTILIZER REC SOIL 7.5-15	0.65	NS	0.22	NS	20.16	0.00	0.92	NS
ANTHESIS FERTILIZER REC SOIL 15-30	1.55	NS	2.31	NS	0.50	NS	1.06	NS
ANTHESIS FERTILIZER REC SOIL 30-60	1.08	NS	4.49	0.06	5.66	0.06	0.97	NS
ANTHESIS FERTILIZER REC SOIL TOT	21.69	0.00	4.44	0.06	2.63	NS	0.71	NS
HARVEST FERTILIZER REC MIN N 0-30	0.10	NS	8.94	0.01	30.05	0.00	9.48	0.02
HARVEST FERTILIZER REC MIN N 30-75	0.22	NS	151.10	0.00	62.08	0.00	42.71	0.00
HARVEST FERTILIZER REC MIN N 75-90	0.06	NS	7.50	0.02	14.22	0.01	4.74	0.07
HARVEST FERTILIZER REC MIN N TOT	0.04	NS	24.87	0.00	46.58	0.00	19.77	0.00
HARVEST FERTILIZER REC IMM N 0-30	0.19	NS	0.59	NS	89.89	0.00	14.28	0.01
HARVEST FERTILIZER REC IMM N 30-75	3.30	NS	1.90	NS	26.85	0.00	1.78	NS
HARVEST FERTILIZER REC IMM N TOT	1.18	NS	1.08	NS	114.00	0.00	7.36	0.02
HARVEST FERTILIZER REC SOIL 0-30	0.22	NS	0.66	NS	151.10	0.00	22.69	0.00
HARVEST FERTILIZER REC SOIL 30-75	2.59	NS	3.91	0.08	22.88	0.01	2.00	NS
HARVEST FERTILIZER REC SOIL TOT	1.07	NS	1.69	NS	134.60	0.00	11.21	0.01
HARVEST PLANT+SOIL FERTILZER REC	0.67	NS	0.80	NS	16.93	0.01	7.77	0.03
ANTHESIS PLANT+SOIL FERTILIZER REC	12.25	NS	1.13	NS	19.26	0.01	1.39	NS

NS means not significant at the 10% level

APPENDIX 3b LEAST SIGNIFICANT DIFFERENCES (5%)

TEST SUBJECT	LSD 5% WATER	LSD 5% SUBPLOTS OVER ALL	LSD 5% SUBPLOTS SAME WATER	LSD 5% SUBPLOTS DIFFERENT WATER
GRAIN % N	NS	0.07	0.17	0.30
PLANT DENSITIES	NS	3.34	8.19	15.12
HEAD NUMBERS	7.24	4.01	9.82	10.77
GRAIN PER HEAD	0.25	NS	NS	NS
GRAIN YIELDS	NS	222.44	544.88	817.05
HARVEST N UPTAKE	NS	6.69	16.38	25.42
WEEK 1 N UPTAKE	NS	NS	NS	NS
WEEK 2 N UPTAKE	NS	3.95	9.69	18.19
WEEK 3 N UPTAKE	NS	8.90	21.81	41.95
WEEK 4 N UPTAKE	NS	9.77	23.92	31.01
WEEK 5 N UPTAKE	NS	18.29	44.80	48.27
WEEK 1 % N	NS	0.19	0.47	0.54
WEEK 2 % N	NS	0.21	0.53	0.73
WEEK 3 % N	NS	0.42	1.03	1.14
WEEK 4 % N	NS	0.45	1.11	1.28
WEEK 5 % N	NS	0.36	0.87	1.15
GRAVIMETRIC SOIL MOISTURE 0-15 CM	3.35	1.23	3.01	4.14
GRAVIMETRIC SOIL MOISTURE 15-30 CM	3.88	NS	NS	NS
GRAVIMETRIC SOIL MOISTURE 30-60 CM	NS	NS	NS	NS
CROP FERTILIZER % RECOVERY HARVEST	NS	5.62	13.76	20.14
WEEK 1 FERTILIZER % RECOVERY	NS	2.92	7.14	8.40
WEEK 2 FERTILIZER % RECOVERY	8.55	5.86	14.36	13.27
WEEK 3 FERTILIZER % RECOVERY	19.17	7.13	17.46	22.80
WEEK 4 FERTILIZER % RECOVERY	NS	5.70	13.96	25.30
WEEK 5 FERTILIZER % RECOVERY	14.90	13.58	33.27	27.84
ANTHESIS FERTILIZER REC MIN N 0-7.5	6.66	6.93	16.97	13.72
ANTHESIS FERTILIZER REC MIN N 7.5-15	NS	NS	NS	NS
ANTHESIS FERTILIZER REC MIN N 15-30	NS	NS	NS	NS
ANTHESIS FERTILIZER REC MIN N 30-60	1.22	1.15	2.82	2.34

APPENDIX 3b (cont.) LEAST SIGNIFICANT DIFFENCENCES (5%)

TEST SUBJECT	LSD 5% WATER	LSD 5% SUBPLOTS OVER ALL	LSD 5% SUBPLOTS SAME WATER	LSD 5% SUBPLOTS DIFFERENT WATER
ANTHESIS FERTILIZER REC MIN N TOT	12.44	13.02	31.88	25.75
ANTHESIS FERTILIZER REC IMM N 0-7.5	9.27	5.15	12.61	12.86
ANTHESIS FERTILIZER REC IMM N 7.5-15	NS	4.26	10.44	13.90
ANTHESIS FERTILIZER REC IMM N 15-30	NS	NS	NS	NS
ANTHESIS FERTILIZER REC IMM N 30-60	NS	NS	NS	NS
ANTHESIS FERTILIZER REC IMM N TOT	NS	5.89	14.44	21.71
ANTHESIS FERTILIZER REC SOIL 0-7.5	6.01	9.99	24.48	18.32
ANTHESIS FERTILIZER REC SOIL 7.5-15	NS	6.59	16.13	18.62
ANTHESIS FERTILIZER REC SOIL 15-30	NS	NS	NS	NS
ANTHESIS FERTILIZER REC SOIL 30-60	NS	NS	NS	NS
ANTHESIS FERTILIZER REC SOIL TOT	NS	NS	NS	NS
HARVEST FERTILIZER REC MIN N 0-30	1.57	0.65	1.58	1.93
HARVEST FERTILIZER REC MIN N 30-75	0.30	0.29	0.72	0.59
HARVEST FERTILIZER REC MIN N 75-90	0.03	0.02	0.04	0.04
HARVEST FERTILIZER REC MIN N TOT	1.68	0.86	2.11	2.25
HARVEST FERTILIZER REC IMM N 0-30		1.97	4.83	18.78
HARVEST FERTILIZER REC IMM N 30-75	NS	3.38	8.29	10.83
HARVEST FERTILIZER REC IMM N TOT	NS	3.60	8.82	20.86
HARVEST FERTILIZER REC SOIL 0-30	NS	1.78	4.35	19.83
HARVEST FERTILIZER REC SOIL 30-75	NS	4.45	10.91	11.37
HARVEST FERTILIZER REC SOIL TOT	NS	3.85	9.43	22.28
HARVEST PLANT+SOIL FERTILZER REC	NS	6.01	14.73	31.68
ANTHESIS PLANT+SOIL FERTILIZER REC	NS	14.45	35.39	29.63

NS means not significant at the 5% level

APPENDIX 4

CLIMATE DATA -- ELLERSLIE METEOROLOGICAL STATION

DAY	MAY		JUNE		JULY		AUGUST	
	Max. Temp C	Prec. (mm)	Max. Temp C	Prec. (mm)	Max. Temp C	Prec. (mm)	Max. Temp C	Prec. (mm)
1	--		28.8		23.5		26.0	0.2
2	--		23.3		23.4	10.0	26.5	
3	--		19.7		18.5	0.2	27.0	6.8
4	--		18.8	1.0	17.3	6.8	21.9	3.8
5	--		20.9		17.0	1.0	17.5	7.4
6	--		24.3		19.4		23.5	
7	--		23.2	4.8	22.0	0.2	25.5	1.4
8	--		21.7		24.7	6.2	20.2	
9	--		23.3		18.2	10.0	19.5	
10	--		27.0	0.4	21.2		23.9	
11	--		16.4	1.8	16.7	2.4	28.5	
12	--		18.3		14.4	6.0	26.7	
13	--		17.7	5.0	14.9	0.2	24.7	
14	--		18.4	3.4	20.1		20.7	
15	--		11.0	15.6	18.6	13.8	18.3	
16	--		18.8		12.8	13.4	19.6	
17	--		26.0	0.2	16.4	25.4	25.6	
18	--		22.4	0.6	19.5	2.2	28.5	
19	--		16.3	15.6	21.2	2.0	17.2	
20	--		20.2		25.5		22.5	
21	--		21.9		26.6		19.4	
22	SEEDING COMMENCED		22.5		25.7	0.2	23.8	
23	17.1		25.0	0.4	17.3	12.0	27.8	
24	24.0		20.6	6.8	21.7	2.4	17.5	3.8
25	28.5		17.3	13.9	20.2	0.2	16.3	1.8
26	31.6		17.6		19.4		22.0	
27	26.6		20.3		18.0		26.3	
28	30.0		22.7		20.0	0.2	28.8	
29	30.6		16.8	1.4	17.2	0.4	23.9	0.4
30	31.6		19.7		19.6	5.8	22.1	
31	24.3				21.7		20.2	
				70.9		128.0		25.6
								224.5

APPENDIX 5 HARVEST DATA

MOISTURE (cm / week)	FERTILIZER TREATMENT	PLANTS / m ROW	HEADS / m ROW	GRAIN (g) /HEAD	GRAIN YIELD (kg/ ha)	GRAIN % N	CROP N UPTAKE (kg N / ha)	CROP FERT. REC (%)
NO	CON	46	51	0.844	2142	1.68	48.0	
	BI	46	62	0.807	2488	1.93	70.1	35.5
	DB	28	64	1.236	3980	1.91	105.2	70.4
1.0	CON	36	42	1.358	2851	1.52	55.1	
	BI	40	60	1.181	3513	1.73	81.7	47.0
	DB	34	69	1.217	4464	1.87	107.7	67.9
1.5	CON	31	43	1.558	3329	1.47	63.7	
	BI	33	47	1.537	3562	1.65	75.2	37.2
	DB	25	51	1.659	4214	1.76	94.9	65.8
2.0	CON	40	44	1.324	2928	1.30	50.0	
	BI	39	52	1.540	3947	1.49	76.6	41.7
	DB	25	50	1.790	4478	1.56	92.3	57.0
2.5	CON	33	40	1.500	2869	1.43	52.7	
	BI	34	54	1.712	4597	1.41	95.8	46.2
	DB	31	63	1.593	5005	1.57	99.4	69.4
Field	CON	40	44	1.302	2829	1.39	54.5	
	BI	41	48	1.404	3381	1.56	73.0	32.8
	DB	35	68	1.465	4951	1.60	114.6	71.9
Mean	CON	38	44	1.314	2825	1.46	54.0	
	BI	39	54	1.363	3581	1.63	78.7	40.1
	DB	30	61	1.493	4515	1.71	102.4	67.0

APPENDIX 6 Weekly crop N uptakes, % N and %fertilizer recovery

SAMPLE WEEK	CROP CHARACTER	WATER APPLIED (cm water per week until anthesis) NO CON	NO BI	NO DB	1.0 CON	1.0 BI	1.0 DB	1.5 CON	1.5 BI	1.5 DB	2.0 CON	2.0 BI	2.0 DB
	Kg N / ha	5.67	7.23	6.63	6.74	7.30	6.42	5.39	6.09	5.89	9.04	11.27	11.14
1	plant % N	5.39	5.52	5.75	5.48	5.33	5.69	5.59	5.64	5.89	5.56	5.60	5.88
	% fert. rec.		0.05	4.37		0.65	3.82		0.14	2.79		2.98	7.07
	Kg N / ha	13.81	18.82	20.52	23.56	27.50	34.47	23.30	20.25	24.43	41.69	38.09	42.53
2	plant % N	4.75	5.03	5.44	5.06	5.11	5.49	5.28	5.41	5.51	4.97	5.22	5.32
	% fert. rec.		0.31	18.93		4.51	24.29		2.74	15.89		14.34	29.14
	Kg N / ha	29.22	27.47	56.65	37.26	44.99	67.14	41.53	39.47	53.34	41.30	71.58	75.46
3	plant % N	3.73	3.43	4.66	3.71	3.78	4.56	4.50	4.60	4.69	2.86	3.65	4.09
	% fert. rec.		0.98	45.93		11.92	41.06		12.52	31.75		44.07	59.29
	Kg N / ha	25.88	36.34	68.23	54.48	61.85	93.41	50.75	61.60	88.53	51.54	84.50	105.05
4	plant % N	1.91	2.35	3.23	2.47	3.07	3.79	2.97	3.25	3.70	1.99	2.57	2.70
	% fert. rec.		2.86	54.21		40.74	66.43		25.70	51.18		43.57	70.07
	Kg N / ha	32.19	25.58	76.37	48.53	67.51	108.07	71.18	69.70	116.33	54.11	61.51	114.46
5	plant % N	1.44	1.55	2.47	1.74	2.32	2.96	2.18	2.46	2.86	1.77	1.93	2.61
	% fert. rec.		1.17	59.06		36.01	63.72		32.90	73.51		44.53	72.35

APPENDIX 6 (continued)

SAMPLE WEEK	CROP CHARACTER	Water applied (cm water per week until anthesis) 2.5 CON	2.5 BI	2.5 DB	FIELD CON	FIELD BI	FIELD DB	MEAN CON	MEAN BI	MEAN DB
	Kg N / ha	11.76	12.49	12.58	8.45	7.59	8.86	7.84	8.66	8.58
1	plant % N	5.19	5.61	5.76	4.94	5.01	5.41	5.36	5.45	5.73
	% fert. rec.		5.63	10.33		0.59	6.34		1.67	5.78
	Kg N / ha	28.71	41.28	35.52	25.97	22.44	38.10	26.17	28.06	32.59
2	plant % N	4.95	4.95	5.34	4.96	4.86	5.26	4.99	5.10	5.39
	% fert. rec.		23.98	26.60		7.16	22.34		8.84	22.86
	Kg N / ha	60.36	63.39	72.41	44.92	51.41	63.65	42.43	49.72	64.77
3	plant % N	3.52	3.80	4.25	3.33	4.61	4.53	3.61	3.98	4.46
	% fert. rec.		39.56	63.03		21.62	45.78		21.78	47.80
	Kg N / ha	54.61	84.75	88.64	44.14	61.47	95.88	46.90	65.08	89.95
4	plant % N	2.30	2.79	3.16	2.03	2.60	3.61	2.28	2.77	3.36
	% fert. rec.		49.56	77.76		36.39	66.76		33.14	64.40
	Kg N / ha	64.71	87.05	97.93	49.46	68.55	98.85	53.36	63.31	102.00
5	plant % N	1.98	2.55	2.65	1.54	1.89	2.29	1.78	2.12	2.64
	% fert. rec.		41.01	72.54		39.18	63.04		32.46	67.37

APPENDIX 7 N-15 FERTILIZER RECOVERIES (%) IN THE SOIL AT ANTHESIS

SOIL DEPTH (cm)	NITROGEN COMPONENT	MOISTURE REGIME (cm water per week until anthesis) NO		1.0		1.5		2.0		2.5		FIELD		MEAN	
		BI	DB	BI	DB	BI	DB	BI	DB	BI	DB	BI	DB	BI	DB
0-7.5	Mineral N	19.6	13.6	7.2	13.7	8.1	6.1	2.0	1.9	5.7	0.7	3.3	0.4	7.7	6.0
	Immobilized N	13.9	5.0	11.3	7.5	22.6	5.3	23.9	9.8	17.8	8.1	42.0	9.8	21.9	7.6
	Total N	33.5	18.6	18.6	21.2	30.8	11.4	25.9	11.7	23.5	8.8	45.4	10.2	29.6	13.6
7.5-15	Mineral N	1.5	16.7	0.8	5.8	1.0	9.0	0.4	6.0	0.7	2.5	0.6	0.7	0.8	6.8
	Immobilized N	2.3	3.9	1.7	13.3	4.3	11.7	4.1	5.9	3.4	16.5	7.5	8.8	3.9	10.0
	Total N	3.8	20.6	2.5	19.2	5.3	20.7	4.5	11.9	4.1	19.0	8.1	9.5	4.7	16.8
15-30	Mineral N	1.5	0.5	0.8	0.6	0.9	0.5	0.4	0.7	0.7	1.2	0.1	1.3	0.7	0.8
	Immobilized N	4.5	2.1	8.9	2.4	3.0	2.3	2.7	1.8	2.5	1.7	4.0	8.3	4.3	3.1
	Total N	6.0	2.6	9.7	3.0	3.9	2.8	3.2	2.4	3.2	2.9	4.1	9.6	5.0	3.9
30-60	Mineral N	6.0	2.0	2.5	0.6	0.9	1.2	0.4	0.2	0.9	0.2	0.1	0.6	1.8	0.8
	Immobilized N	8.2	3.9	5.5	0.3	4.9	3.2	3.1	1.5	2.9	1.1	2.1	2.1	4.4	2.0
	Total N	14.1	5.9	8.0	0.8	5.8	4.3	3.5	1.7	3.8	1.3	2.2	2.7	6.3	2.7
Total depth	Mineral N	28.5	32.8	11.3	20.7	10.9	16.8	3.3	8.8	7.9	4.6	4.1	2.9	11.0	14.4
	Immobilized N	28.9	14.8	27.4	23.0	34.8	22.3	33.8	18.9	26.6	27.3	55.6	29.0	34.5	22.5
	Total N	57.4	47.6	38.8	43.6	45.7	39.0	37.1	27.7	34.5	31.9	59.8	32.0	45.5	37.0

APPENDIX 8 N-15 FERTILIZER RECOVERIES (%) IN THE SOIL AT HARVEST

SOIL DEPTH (cm)	NITROGEN COMPONENT	MOISTURE REGIME (cm water per week until anthesis) NO		1.0		1.5		2.0		2.5		FIELD		MEAN	
		BI	DB	BI	DB	BI	DB	BI	DB	BI	DB	BI	DB	BI	DB
0-30	Mineral N	6.7	1.7	1.6	0.8	3.0	0.5	0.9	0.7	1.1	0.8	0.9	1.0	2.4	0.9
	Immobilized N	48.2	34.7	42.7	27.3	39.4	37.0	45.9	32.4	35.6	32.0	43.0	45.6	42.5	34.8
	Total N	55.0	36.4	44.3	28.2	42.4	37.5	46.8	33.0	36.7	33.8	43.8	46.6	44.8	35.9
30-75	Mineral N	5.0	0.2	0.3	0.1	0.4	0.0	0.1	0.2	0.2	0.0	0.1	0.1	1.0	0.1
	Immobilized N	22.4	7.6	12.8	9.8	11.9	3.9	9.2	3.0	10.0	4.9	8.5	4.7	12.5	5.6
	Total N	27.5	7.8	13.1	9.9	12.3	3.9	9.3	3.1	10.3	4.9	8.6	4.7	13.5	5.7
75-90	Mineral N	0.09	0.02	0.01	0.01	0.04	0.00	0.01	0.01	0.00	0.00	0.02	0.01	0.03	0.01
Total soil	Mineral N	11.8	1.9	2.0	1.0	3.4	0.5	1.1	0.8	1.3	0.8	1.0	1.1	3.4	1.0
	Immobilized N	70.7	42.3	55.5	37.2	51.2	40.4	55.0	35.3	45.6	33.8	51.5	50.2	54.9	40.5
	Total N	82.4	44.2	57.5	38.1	54.7	40.9	56.1	36.2	47.0	34.7	52.4	51.3	58.3	41.5

APPENDIX 9 N-15 FERTILIZER RECOVERIES (%) IN THE SOIL+PLANT SYSTEM

SAMPLE DATE	SYSTEM COMPONENT	MOISTURE REGIME (cm water per week until anthesis) NO		1.0		1.5		2.0		2.5		FIELD		MEAN	
		BI	DB	BI	DB	BI	DB	BI	DB	BI	DB	BI	DB	BI	DB
Anthesis	Plant	1.2	59.1	36.0	63.7	32.9	73.5	44.5	72.4	41.0	72.5	39.2	63.0	32.5	67.4
	Soil	60.1	47.6	38.8	43.6	45.7	39.0	37.1	27.7	34.5	31.9	59.8	32.0	45.5	37.0
	Total	61.2	106.7	74.8	107.4	78.6	112.5	81.6	100.0	75.5	104.4	99.0	95.0	78.0	104.4
Harvest	Plant	35.5	70.4	47.0	67.9	37.2	65.8	41.7	57.0	46.2	69.4	32.8	71.9	40.1	67.0
	Soil	82.4	44.2	57.5	38.1	54.7	40.9	56.1	36.2	47.0	34.7	52.4	51.3	58.3	41.5
	Total	117.9	114.6	104.5	106.0	91.9	106.7	97.7	93.1	93.2	104.0	85.2	123.2	98.4	108.5